Master Thesis

The Aviation Fuel and the Passenger Aircraft for the Future – Batteries

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Abstract

This thesis covers the feasibility of batteries as a mechanism of energy storage in commercial air transportation in two main aspects, technical and economical. Along with this, it also aims to show what kind of changes should be implemented and what challenges faces this alternative. In order to achieve that, some simplified models have been implemented in aircraft design software, and also some simplifying assumptions have been made. A futuristic scenario is contemplated, and with the expected battery technology, possibilities of batteries are analyzed, taking the current A320 model as the basis of a fair and revealing comparison. This alternative sheds discouraging results. A hypothetical A320 equipped with futuristic Li-S batteries would have a range of just 320 km if safety requirements are respected (loiter and alternative airport reserves) being its DOC around ten times larger than the original's. It is then found that, in order to respect payload and range requirements of the A320, battery technology needs to reach values of specific energy and energy density higher than 8 MJ/Kg, and 2.2 MJ/kg respectively, much greater than the futuristic battery Li-S ones. As a conclusion, it can be said that it is technically possible to fly very short distances with batteries, but this solution is not a real alternative in the short and middle term by itself. In consequence, other kinds of technologies must be considered in order to change air transportation in a more ecological way.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

The Aviation Fuel and the Passenger Aircraft for the Future – Batteries

Task for a *Master Thesis*

Background

Our planet is a finite entity and as such also energy stored on it is finite. Our planet offers carbon-based fossil fuels (coal, oil, and gas) ready to be used. Burning these fuels releases CO2 into the finite atmosphere of our planet which leads to global warming. The question is simply, if taking from one limited reservoir and releasing into another limited reservoir may empty the first reservoir or may overfill the second reservoir within the foreseeable future. Whatever happens first (a reservoir being empty or overfilled) will be the limiting factor for the system. What will happen first? We live in a growing fossil fuel economy where emptying and filling takes place at an increasing rate. At what speed do we want to approach the inevitable. The question is will fossil fuel get too scarce and thus too expensive to be used? Or will CO2 levels reach climate effects (droughts, flooding, severe storms) the earth's growing population cannot cope with? Air transportation is one part of the growing carbon economy and has to carry its share in problem solving. The related research question for aviation is here: What is the best fuel strategy for passenger air transport in a post-fossil fuel era? In a post-fossil fuel era energy will come from renewable energy (wind, solar, bio-mass ...). Most forms of renewable energy (wind, solar ...) will be available primarily as electricity. Electrical energy could be stored in batteries; alternatively, energy could also be converted into a chemical form (gaseous or liquid fuel) to be stored on board. Other forms of renewable energy (like bio mass) could be converted directly to drop-in fuel. The best fuel option for passenger aircraft becomes visible only if aircraft are designed with all iterations and snowball effects for the energy option selected. **Three Master Theses have been set up as a trilogy** to investigate this:

The Aviation Fuel and the Passenger Aircraft for the Future –
a) Batteries, b) Hydrogen, c) Bio Fuel, Synthetic Fuel

a) Batteries: In a post-fossil fuel era (regenerative) energy will exist first of all as electricity. To avoid energy conversions (always going along with energy losses), it

makes sense to try direct storage and use of electricity. But batteries are heavy – a contradiction to the first rule in aircraft design: "Watch the weight!"
b) Hydrogen: Hydrogen production from electricity is simple through electrolysis and today with 70 % already quite efficient. Hydrogen powered aircraft have already been built and have been flown successfully. Hydrogen is a tested technology in aviation that will work. It makes sense to look again at this concept with new ideas to limit investment and to avoid a bulky aircraft.
c) Bio Fuel, Synthetic Fuel: The best fuel is the fuel we have today. Kerosene has a high energy density by weight and by volume. Drop-in fuels are those renewable fuels which can be blended with today's fuel and can be utilized in the current infrastructure and with existing equipment. Drop-in fuels generally have similar parameters and can be blended at various ratios up to 100 %. The challenge here is with availability of bio fuels compared to the huge demand. In a post-fossil fuel era synthetic fuel will come from a power to liquid (PTL) process based on regenerative energy. Will it be possible to scale up the processes fast enough and to deliver at a compatible price? The challenge here is the fuel and not the aircraft.

Among the three options, **batteries** have the advantage that they do not have any emissions in flight. Since WWII electricity has been in use on airplanes to drive onboard systems. As such, electric systems have been in competition with pneumatic and hydraulic systems. All three are known as secondary power systems. There has been a clear trend towards an increase use of electric systems. On so called "all electric airplanes" this trend has reached a point where almost everything except for the propulsion system is electric. Consequently, an extrapolation can be made, thinking about a future where airplanes would be fully electrical – including propulsion.

Task

Task of this Master Thesis is to study and analyze a battery-powered A320. The aircraft shall have the same requirements as the original kerosene-fueled aircraft. The subtasks are:

- Data collection (current and projected) of batteries.
- Comparison between battery and kerosene fuel tank as energy storage.
- Discussion of the main aircraft design differences: battery and kerosene versions.
- Analysis and comparison of hydrogen-fueled aircraft with OPerA.
- Discussion of the economics of a battery-powered aircraft.

The report has to be written in English based on German or international standards on report writing.

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Symbols

A	Aspect ratio
A_8	Outlet area of the engine
C_D	Drag coefficient
C_{D0}	Zero-lift drag coefficient
C_L	Lift coefficient
$C_{L,max,L}$	Maximum lift coefficient for landing configuration
$C_{L,LOF}$	Lift coefficient in Lift-Off configuration
c_p	Specific heat constant of the air, pressure constant
D	Drag
E	Aerodynamic glide ratio, also called aerodynamic efficiency
En	Remaining energy in batteries
e	Oswald factor
G	Airflow
g	Gravity
K_{APP}	Approach constant
k_{TO}	Take-off constant
k_l	Landing constant
L	Lift
M_i	Mach number of air in stage i in the engine
m	Mass
m_F	Fuel Mass
m_{ML}	Landing Mass
m_{OE}	Operative Empty Mass
m_{PL}	Payload Mass
m_{TO}	Take-Off Mass
m_{MTO}	Maximum Take-Off Mass
n_E	Number of engines

P_{bat}	Power that batteries provide
P_{fan}	Power that the fan receives
P_{flight}	Power necessary to fly in cruise phase
$P_{airflow}$	Power injected to the airflow along the engine
P_i	Pressure of air in stage i in the engine
P_{it}	Stagnant pressure of air in stage i in the engine
R	Range
R_g	Air gas constant
S_W	Wing area
s_e	Specific energy of batteries
s_{TOFL}	Take-Off Field Length
s_{TOG}	Distance of Take-Off Ground roll
T	Overall thrust
T_{TO}	Take-Off thrust
T_{flight}	Thrust necessary to maintain the flight
T_i	Temperature in stage i in the engine
T_{it}	Stagnant temperature in stage i in the engine
t	Endurance
V	Flight velocity
V_i	Air velocity in stage i in the engine
V_{LOF}	Lift-Off velocity
W	Weight
W_{bat}	Weight of batteries
W_{OEW}	Operative Empty Weight
W_{PL}	PayLoad weight

Greek Symbols

α	Angle of attack
γ	Climb angle
γ_g	Relation of specific heat constants of air
η_f	Fan efficiency
η_p	Propulsive efficiency
π_f	Pressure ration of the fan
ρ	Air density
ρ_0	Air density at sea level
σ	Quotient of air density at some altitude and air density at sea level
τ_f	Specific power given to the air, coming from the fan
φ	Aerodynamic efficiency factor

List of Abbreviations

AC	Alternating Current
ACARE	Advisory Council for Aeronautics Research in Europe
AEA	Association of European Airlines
CO2	Carbon Dioxide
DC	Direct Current
DOC	Direct Operating Cost
FAR	Federal Aviation Regulation
HAW	Hochschule für Angewandte Wissenschaften (Hamburg University of Applied Sciences)
I+D+i	Investigation, Development and innovation
Li-S	Lithium Sulfur
LOF	Lift-Off
NM	Nautical Miles
OPerA	Optimization in Preliminary Aircraft Design, program
PL	PayLoad
TUB	Technical University of Berlin

1 Introduction

1.1 Aims and Motivations

1.1.1 Precedents

After the oil crisis in the 70s, the problem of scarcity of energy in the world suddenly appeared, and endeavours for improving energetic efficiency surged. By that time, the oil price at some point reached values of ten times the pre-crisis ones, and in the long term, the price tripled. A new awareness raised among the old energetic policies, the world was running out of oil, and new predicting theories about when the oil price was going to surge again due to scarcity became more and more famous **(Deffeyes 2006)**. Though, it also has been shown that oil extraction technology improves with time, providing oil industry with new resources to partially cope with this problem. Anyway, there is no doubt that rising oil prices have become one of the biggest problems of the 21st century.

Figure 1.1 Global warming is caused by hydrocarbons consumption, and it is clearly one of the major problems humanity has ever faced.Image taken from **Fundapoyarte (2015)**

On the other hand, another problem related with fossil fuels usage appeared: Global Warming. Carbon dioxide is a natural product of the combustion process, and it is the main responsible of this phenomenon **(Lashof and Ahuja 1990)**. The ecological and economic consequences of Global Warming can be catastrophic: flooding areas, droughts, famine...

These two problems become worse under continuous economic growth, which requires increasing energy consumption to keep running.

Currently, there are efforts to overcome these problems; clean energies and energy saving technologies are being impulsed by different governments around the world, and their costs are steadily falling. If the energetic reality continues this trend, the world could be able to reduce its dependence on fossil fuels sharply in a few decades **(Evans et al. 2009)**.

1.1.2 Fuel Efficiency in Air Transport

Air transportation is one contributing sector to global warming and fuel consumption. It is estimated that this sector is responsible of a 1.7% of global CO2 emissions **(Sausen and Schumann 2000)**. A big amount of efforts have been directed to improve fuel efficiency by reducing weight, making better engines and optimizing procedures. Since the 80s, fuel consumption in industry has decreased around a 30% per person and flight **(Commerce 2005)**, but even though, fuel prices still being the major cost source for air companies.

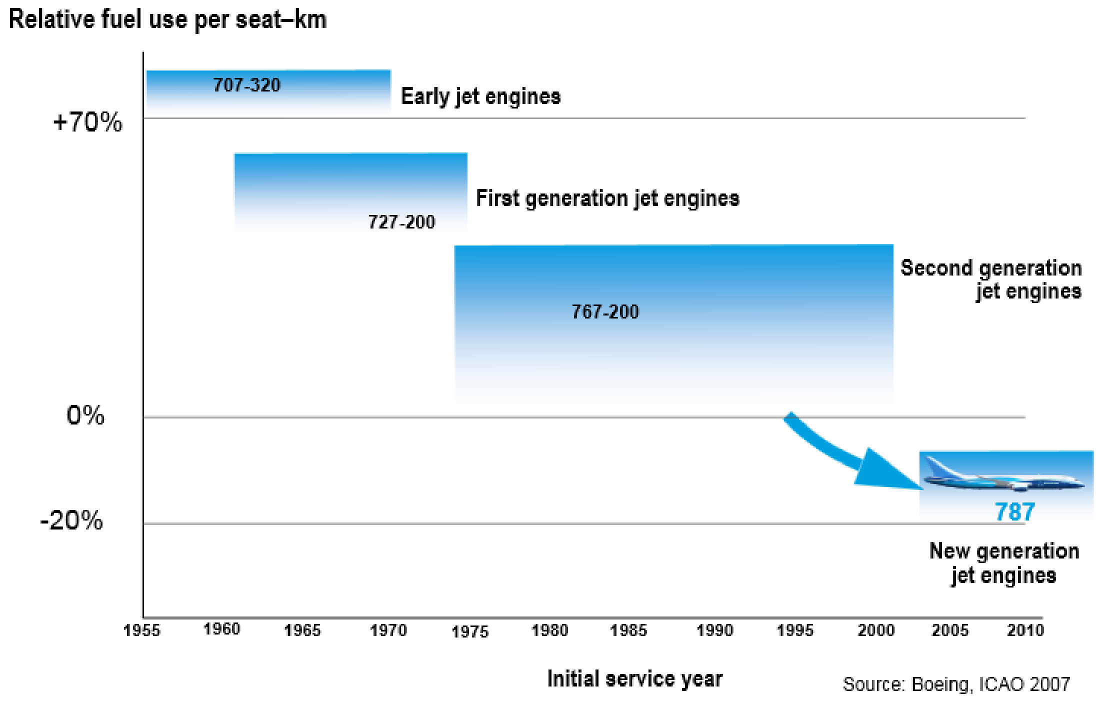

Figure 1.2 Efficiency in aircraft has been steadily improving along the years.

Air transport faces a big problem concerning ecology: The only practical possibility of being more ecological has been saving fuel with new technology and materials. This means that, until now, there has been no real alternative of energy storage rather than fuel. If the economic and ecological trends continue in the same direction, air transport is in risk of decreasing soon or later. Another kind of transports as high speed trains are becoming harder competitors because they have the advantage of using electricity instead of fuel.

1.1.3 Solution under Study

Given the information exposed, it is clear that there is a necessity of studying a different ways to power aircraft. The purpose of this work is the study of a particular alternative of energy storage in an aircraft, batteries.

Batteries have surged in the last years as a feasible alternative to power other kind of transportations, like automobile transportation. Decreasing costs of manufacturing and the improvement of technology (endurance, corrosion, properties loosing...) have made possible this alternative.

There is now a huge investment in battery technology because of this **(IHS 2011)**. The general development of electronics is also a big source of investment in I+D+i for batteries.

The consequence is a predictable improvement of battery technology and also a cost reduction **(Lux et al. 2010)**.

Figure 1.3 The Airbus E-fan is a modern project of a battery powered airplane. It is only a prototype for now, but it is a first important step in this direction.Image taken from **Griffiths (2014)**

1.2 Objectives

This work aims to show interesting information about the possibility of building a battery powered aircraft. The aircraft used will be based on the A320, a very common short-medium haul aircraft used in commercial transport.

One first objective is to show the design changes it would be necessary to implement in the aircraft in order to adapt it to the new systems. This changes will cause that the whole aircraft would be subject to a new re-optimization, causing major changes.

The second objective is to provide a reliable comparison between the battery powered A320 and the original one, so it will be possible to consider the real technological distance between the two possibilities.

The third objective is to show the technical and economical viability of batteries as a energy storage method in air transportation. At the same time this point will be considered in three levels: with the current technology and costs, with the predictable technology and costs, and with the theoretical ones necessary to compete with kerosene, answering the following question: How good have to become batteries in order to become a real alternative in aircraft?

The answer of these questions will give us a deep idea of how realistic is the possibility of powering aircraft with batteries.

1.3 Structure of the Thesis

In the two firsts chapters (the current and the following one) an introduction to the own thesis and a brief presentation to the state of the art is performed. From these two chapters the reader can understand the reasons why this thesis has been made, and also start to set the basis of a further understanding, necessary to cope with the rest of the thesis.

In the third chapter, the major changes which are necessary to implement in a battery powered aircraft are exposed. Changes in the engine and in performances are explained, setting ideal equations of the designed airplane. These equations are crucial to understand the operation of the new aircraft, where it is more efficient and how the environment variables affect it.

In the fourth chapter, the main equations of traditional aircraft design are briefly explained, where the matching chart sets a point of design that specifies the size of the engine, the overall weight and the wing area.

In the fifth chapter the software tool, OPerA, is exposed. The processes of how the calculations are done are described without big detail, but it is important to mind the models that are being used so results can be interpreted correctly.

In the sixth chapter results are shown. In the first place it is considered an airplane equipped with battery futuristic technology, and its features and costs are compared with the normal A320. In the second place, it is set a frontier batteries need to surpass in order to become feasible.

Finally, conclusions and future recommendations are set, based on the results of the work and all the process of elaborating it.

2 State of the Art

2.1 Environmental Targets and Goals

Currently there is no particular objective to reduce air transportation emissions in a global scale. The pace of improvement of fuel efficiency is not enough to overcome the continuous growth of the sector, so as a result the overall emissions are steadily increasing. Now the current situation is that countries have to deal with their global emission objectives, and they are free to regulate their own taxation system on emissions in different sectors **(Lee et al. 2013)**.

The European union set a regulation, the European Union Emissions Trading Scheme **(Commission 2005)** which put a taxation on emission within the European Union to all industries by setting an emissions trading system, including air transportation. The Advisory Council for Aeronautics Research in Europe (ACARE) set a very ambitious objective, a 50% CO2 reduction related to air transport is pledged to be archieved by 2020, but it is unlikely to happen given the growing trends **(Muller 2010)**.

This kind of regulations are bound to continue appearing in the following years, pushing all industries (including air transportation) to reduce their CO2 emissions, so it seems it is going to be necessary to act accordingly with it.

2.2 Batteries as an Energy Storage Possibility in Air Transport

Batteries have several advantages and disadvantages. Clearly the main advantage is that it works with electricity, so there are no CO2 emissions in their usage. Also better efficiency and lower weight of the electric associated systems (motors, actuators, mechanical control systems) are other advantages. Finally, it is fair to mention that some kinds of batteries do not need any maintenance.

The disadvantages are safety (discharge events, explosion hazards...) possible pollution (depending on the kind of battery) and a very low specific energy **(BU 2015)** (energy per unit of weight). All hazards will not be considered in this text, but they must be in a deeper study.

Also the capacity loss is one of the typical disadvantages of batteries in general, but some types, such as Lithium ion batteries do not suffer this problem.

For this specific purpose, the current battery technology that fits better with an aircraft is the Lithium polymer cell. It is a kind of battery that has good properties (energy density and specific energy) and is easily adaptable to different devices.

Another kind of technology that doubles the potential of the current lithium polymer cell is the Lithium-Sulfur battery. It is likely to appear in the market in the future, but until now it still

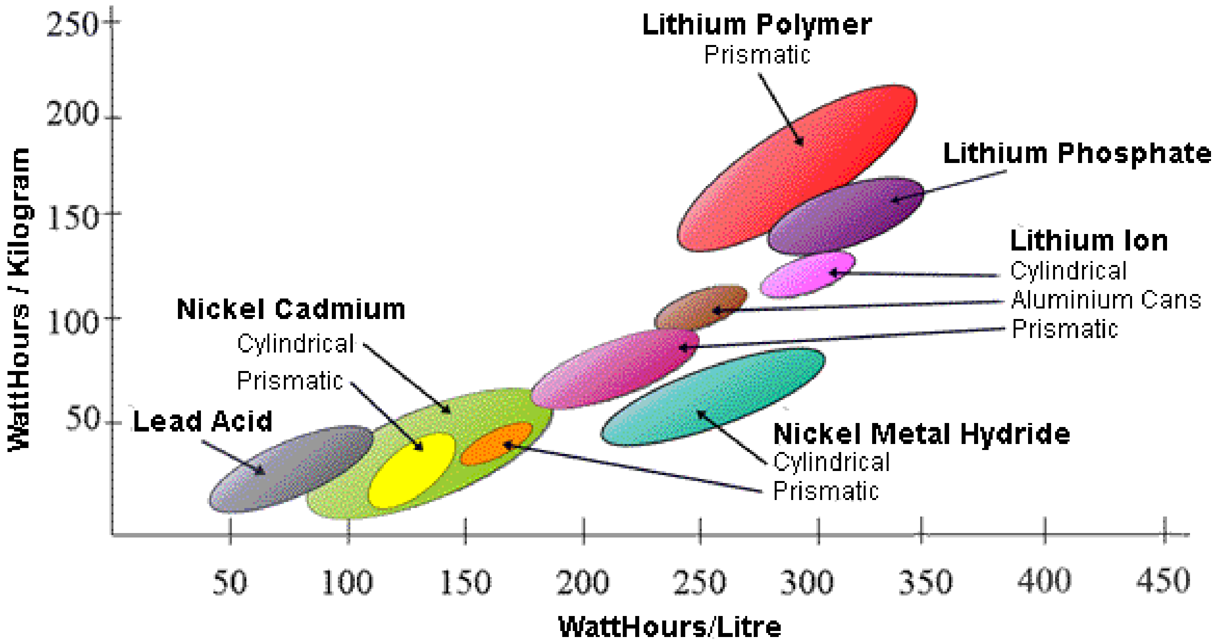

Figure 2.1 Different energy densities and specific energy for different kinds of battery cells, taken from **Electropaedia (2005)**.

under development (**Song et al. 2013**).

2.3 Life-Cycle Assessment: Carbon Footprint of Batteries

Modern Lithium ion batteries are used, for example, in modern electric vehicles, are definitely more eco-friendly than using fuel, providing an environmental burden between 15% and 40% lower than fuel usage in cars (**Notter et al. 2010**). However, it will be necessary to study the particular case of air transportation, because if it is found that the energy consumption from the grid is quite high, batteries might be less eco-friendly than kerosene.

In consequence, it will be necessary to make a deep study in order to answer the question correctly, which will not be addressed in this text.

2.4 Battery and Kerosene Comparison

Specific energy (energy per unit of weight) is a key factor to consider if batteries are a feasible possibility to store energy and use it in air transportation, because energy consumption in an aircraft is highly dependent on weight. The truth is that, if we compare the specific energy of batteries to kerosene (jet fuel), the conclusions are not hopeful (as it is exposed in the next figure).

Also the amount of energy per unit of volume, called energy density, is an important variable to evaluate, because it is also necessary to know if there is space enough in the aircraft for the new energy storage system, and if there is not, then it would be necessary to consider modifying the design in order to accommodate the mentioned system. In this variable the data are not as bad as in the specific energy, but there is still an important gap to close.

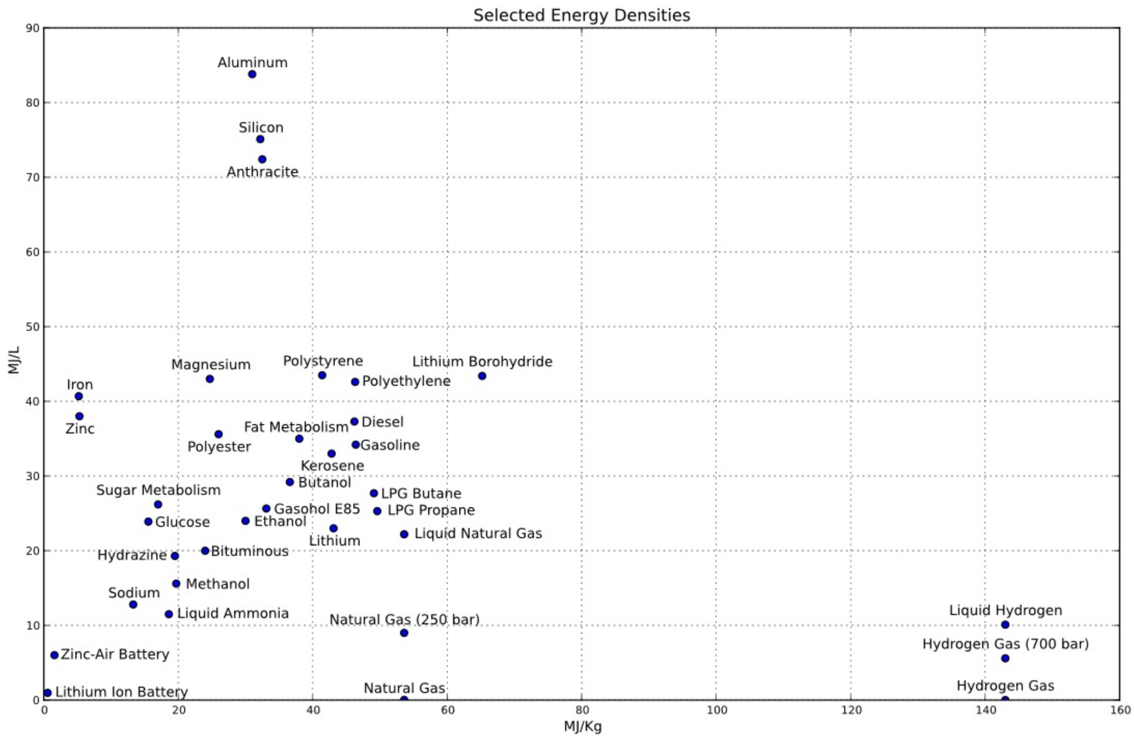

Figure 2.2 Different energy densities and specific energy for different kinds of Energy storage systems, taken from **Dial (2008)**.

The data, in rough numbers, are hopeless for batteries. The specific energy of a battery is two orders of magnitude lower than kerosene, and energy density is one order of magnitude lower. In consequence, it can be foretold that batteries, with current technology, are not a realistic alternative to kerosene. However, there is still hope. An alternative to the current lithium ion batteries is under study: lithium-air batteries have a theoretical specific energy comparable to fuel's, and with the enormous investment on this field, batteries could become a real alternative in the long term **(Girishkumar et al. 2010)**.

There is one last thing to compare, and it is cost. Because of the nature of batteries, they can only provide a number of cycles before becoming useless. The data, in rough numbers, show that the price per unit of energy stored is similar in jet fuel and batteries. If we do very simple calculations we find a price of 0.074$/Kwh **(USEIA 2015)** for jet fuel in the wholesale market, and a price of 0.11$/Kwh for electricity in the retail sale market **(TM 2015)**, so the two ways of storing energy have economic figures of the same order of magnitude. There are studies that suggest a Lithium ion battery could last 10000 cycles, boosting then the economic figures to a new order of magnitude **(Wilka 2014)**.

2.4.1 Different Alternatives in Electric Energy Storage

There are an enormous variety of new kinds of batteries that currently are under study, however, only a few are in a privileged position that allows them to have real possibilities to get to the markets relatively soon. Those are going to be exposed as follow:

Fuel Cells

A fuel cell is basically a device that turns chemical energy from a particular fuel into electricity by reacting with an oxidizing agent (for instance oxygen). The main difference with batteries is that fuel cells need a continuous flow of fuel and oxidizer in order to maintain the reaction and so, the output (electricity).

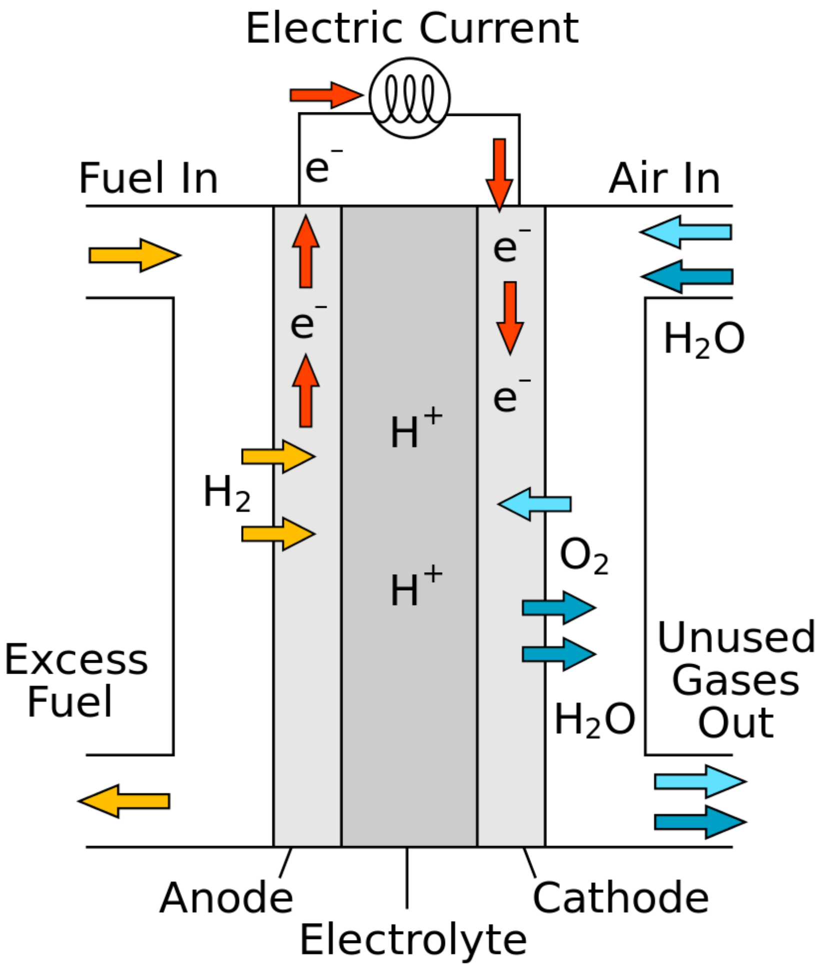

Figure 2.3 Scheme of a fuel cell taken from **Dervisoglu (2012)**.

Because the fuel cell is just the device that allows the exchange between chemical and electrical energy it is important to mind that, for knowing the specific energy of the whole system it is crucial to know the inputs of it (Fuel and oxidizer). The normal fuel cell systems have a good specific energy, but a very low power density (power the system is able to provide per unit of weight) so it is not a good alternative for powerful motors. Though, a big amount of experiments using Hydrogen as a fuel of the fuel cell have been performed in cars, with a very respectable result.

The main problem of this technology is the necessity of installing new facilities for fuel supply, which would mean a huge investment in infrastructure, making it very unattractive for airplanes.

Supercapacitors

They are a very high capacity capacitors, improving capacitors energy density and specific energy by one or two orders of magnitude. Their maximum virtues are the power they can provide, allowing to perform very rapid charge-discharge cycles, and their extended lifetime, much longer than batteries **(Winter and Brodd 2004)**.

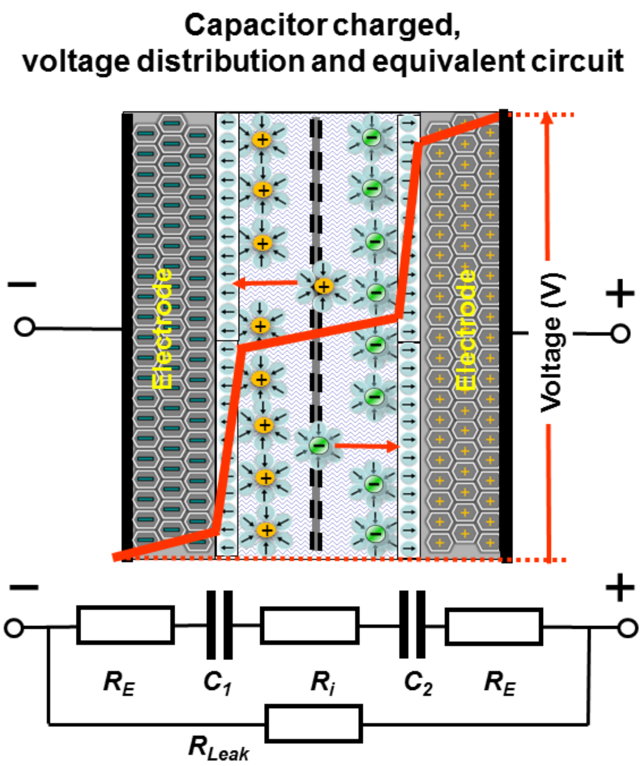

Figure 2.4 Supercapacitor Scheme taken from **Elcap (2013b)**.

Though, their values of specific energy and energy density are, compared to current batteries, comparable, not representing any technological leap. This would force airplanes to be too heavy if they were designed with this kind of technology, so different alternatives must be found for this specific application.

Lithium-Sulfur Battery

This kind of battery is a new alternative that has already been tested, and it is famous for its high specific energy because of the low weight of lithium and the moderate weight of sulfur, allowing it to reach values three times better than current Lithium-ion batteries. Its price is also reasonable, and it can hold 1500 cycles of charge-discharge, so it seems to be a good alternative to consider for a battery powered airplane (**Song et al. 2013**).

Currently, research and development still on progress for this kind of battery, trying to enhance their properties even more, and it is likely that mass production will occur in a close future.

Because all of this, along this work this alternative has been the main technology considered for the design of a battery powered airplane. Its demonstrated values allow to settle the work on a solid basis where affirmations can be made.

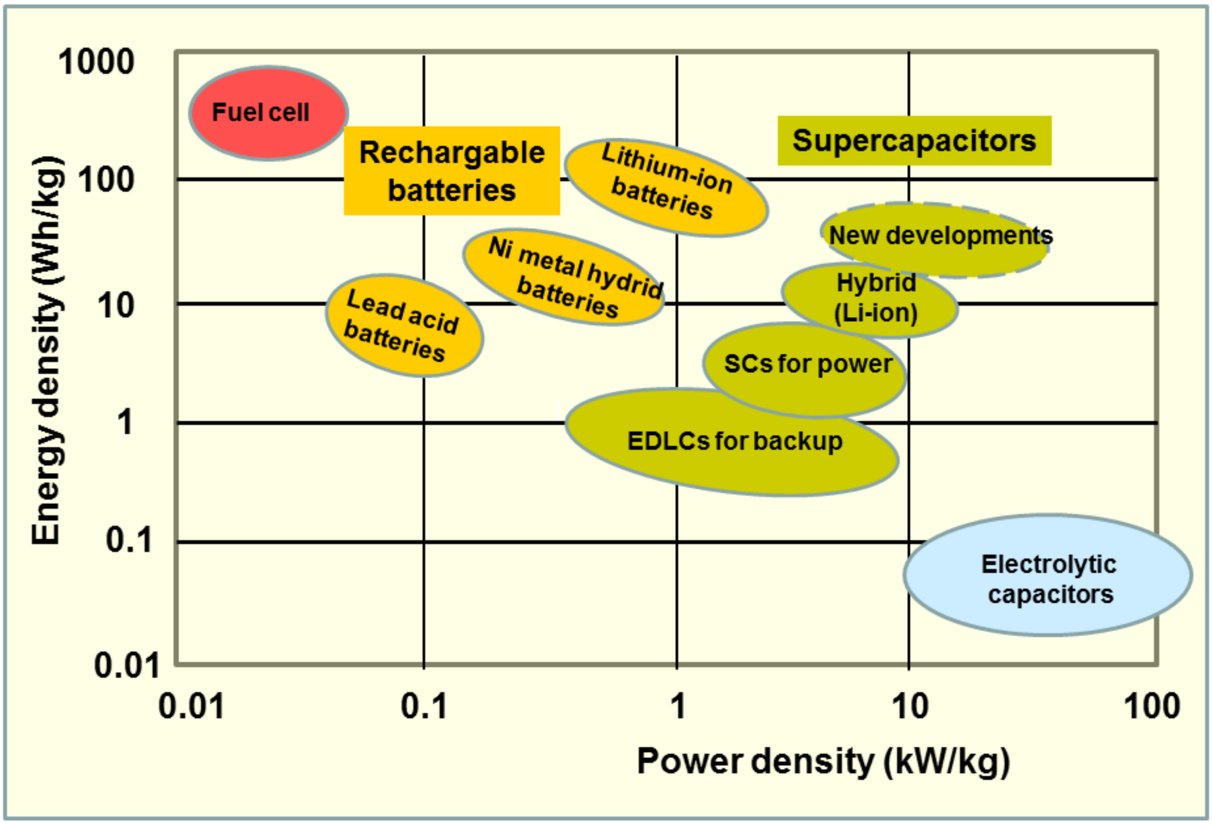

Figure 2.5 Different specific powers and specific energies for different kinds of energy storage systems, taken from **Elcap (2013a)**. Fuel cells would be ideal, but they are not capable of providing large amounts of power.

Graphene Battery

Graphene is a new material which consists of an atomic layer of carbon, with outstanding mechanical and electrical properties. Though, its potential properties still quite unknown, it is true that is has been confirmed its capacity of fast-recharging and its useful life beyond 1000 cycles. Costs also seem to be very low, but it is complicated to make any projection of costs due to the immaturity of the technology (**Mastrolonardo 2014**).

Metal-Air Battery

Metal-Air Batteries are the referent in futuristic batteries. With an anode made of a metal and a cathode made of oxygen coming from air, it allows to achieve great values in specific energy because cathode is not taken into account when calculating it.

Among all kinds of metals that can be used, Lithium and Zinc stand out over the rest. Though, experience in Lithium-ion batteries and the lower specific energy of Zinc-Air batteries leaves us with the Lithium-air battery as the favourite choice (**Lee et al. 2011**).

The main problem of this kind of batteries is that It has not been performed any advanced experiment that demonstrated values and characteristics from them. In consequence, there are only estimations of their practical potential that can vaguely shed some light on its actual possibilities. In conclusion, it is a very futuristic alternative which is unlikely to appear soon, but it can give us an idea of the potential of batteries.

Table 2.1 Features of different energy storage alternatives; **Christensen et al. (2011)**, **Winter and Brodd (2004)** and **Song et al. (2013)**.

Kind of Energy Storage System	Specific Energy(MJ/kg)	Energy Density(MJ/L)
Supercapacitors	0.002-0.006	0.18-0.29
Li-S Battery	1.8	1.26
Graphene Battery	0.23	N/A
Li-Air	2.38-6.48	2.16-5.76

2.5 Battery Powered Aircraft

The consequences of using batteries on an airplane as a power storage system are various. Of course as it has been stated in section 1.2, in the last term it would mean to re-optimize the whole aircraft, so that is going to be done in this work, however, the main changes are the following.

2.5.1 General Aircraft Changes

In the previous section it has been exposed the differences between kerosene and batteries in terms of specific energy and energy density. Because battery properties are much different than kerosene ones, this will mean that dry aircraft weight will drastically change, and it also will be necessary more space to store the batteries. The consequence of these changes will be a change in the landing gear, an improvement of the engines (extra power to deal with the extra induced drag) and increasing space inside the aircraft (probably lengthening the aircraft).

Another consequence could be the insulation of batteries, given the safety hazard associated to them.

2.5.2 Engine Changes

Figure 2.6 Ducted fans will now be the providers of thrust. Image taken from **Varmin (2014)**.

Also the engines will change. Now the aircraft will not be propelled by turbofan jets, but ducted fans powered by electric engines. This could be considered an advantage, because it will not be necessary the core of the turbofan, the jet part. Instead, it will be used a electric engine, which has a great power to weight ratio (8.4 kW/kg), so it seems like there could be a weight saving **(ENSTROJ 2014)** . Though, airplane engines are already very good in that particular area too, (5.67 kW/kg in the A300) and if the data are compared, it seems like there is not going to be any big saving **(Meier 2005)**. But, concerning the engines there is an important advantage that electric motors have compared to turbofans. The energetic efficiency of electric motors is, in rough numbers, twice the efficiency of turbofans (Brayton cycle).

The kind of electric motor to use is clear, the technology used in cars could leave us with the doubt of using a DC brushless motor or an AC induction motor. But if it is analysed closely, it can be seen that DC brushless motor losses efficiency for high power systems, whereas the induction motor does not **(Rippel 2007)**. So, in conclusion, AC induction motor seems the best option. The speed control would be provided by an inverter, which could optimize the performance of the motor changing the frequency**(Burnette and Charles 1972)**. Its efficiency is normally very high, close to unity **(Walde et al. 2011)**.

2.5.3 Performances

One final aspect that is important to mention is that batteries have a big performance disadvantage compared to fuel once they are integrated into an aircraft: when an aircraft is flying, it reduces its weight while is consuming fuel, so energetic efficiency improves with time until before landing, when it reaches the maximum level. This does not happen with batteries, they still weighting even if the energy they store has been consumed. This is a great disadvantage that makes batteries even less advisable for powering an aircraft, especially in long-haul flights, where it would be necessary an enormous battery load.

3 Major Changes in a Battery Powered Aircraft

3.1 Introduction

Before facing the preliminary design of the aircraft it is necessary to comment the main differences in design because of the new way of storing energy. This will lead to face alternative models in contrast to the traditional ones.

The major changes that will be faced are two: On one hand, the engine and how it will provide thrust at different altitudes and velocities, and, on the other hand, the change in Breguet equations because the airplane weight will not change during the flight. Some simple models will be set for each one of the changes, and some explanations and basic conclusions will be extracted from them, shedding some light on the possible viability of a battery powered aircraft.

These two major changes will be necessary in order to face the preliminary design with enough tools that permit us to solve it.

3.2 Changes in the Engine, Equations of the Ideal Ducted Fan

Obviously, when designing an electrically powered aircraft is absolutely necessary to study the variation of thrust given by the change of a traditional turbofan propeller to a fan or a ducted fan. In order to keep things as similar as possible to the original A320, the engine option is going to be a ducted fan, powered by an electrical engine, like shown in the following figure:

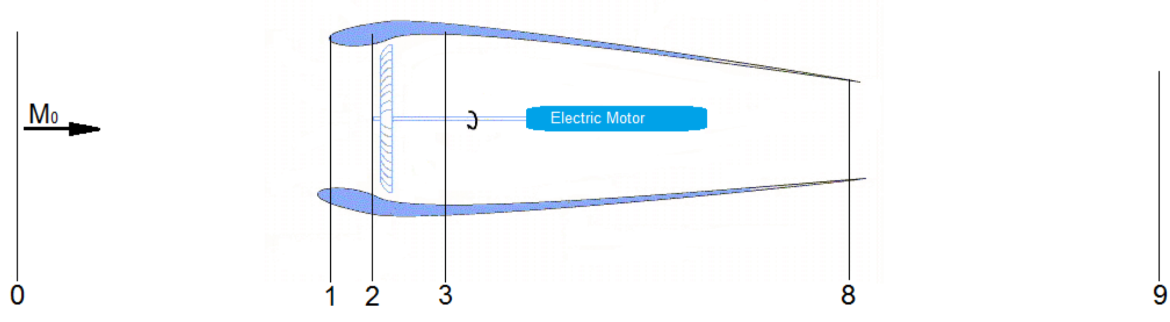

Figure 3.1 Different sections of a ducted fan, taken from **Thomas (2001)** and modified. The notation is taken from the traditional Engine Design criteria.

A ducted fan is, as it can be seen, a fan into a specially designed conduct, very similar to a turbofan duct. In elemental terms, it is a turbofan without the jet, and therefore being powered by a different source of power (an electric motor in this case). The mission of the fan will be to provide power to the air by increasing its pressure, so, as it will be seen, it can be treated like a compressor (in fact it is).

Because there are no big amounts of data available of big ducted fans, it is going to be stated a simple ideal model that assumes there are no losses apart from the propulsive efficiency and the electrical motor efficiency. This means it will be assumed the fan is perfect and does not increase air entropy.

This hypothesis is not conservative, but it permits us to have a good idea of the necessities of power in an electric airplane and it will make calculations much simpler.

3.2.1 Maximum Thrust Calculations

Because notation in thrust and temperature is similar, it is necessary to set an agreement. Temperature will be always named with a numerical sub-index, referring to the temperature at different stages already shown in the previous figure. In contrast, thrust will never be referred with a numerical sub-index but it could be with others (for example $T|_{max}$ will refer to maximum thrust).

Because of the Second Newton Law, it can be said that thrust is given by

$$T = G(V_9 - V_0) \tag{3.1}$$

Where V_9 is the exhaust gases velocity, V_0 is the fight velocity and G is the mass of air consumed by the engine per unit of time, named air flow. It will be considered that the engine has its own limit when reaches its critical conditions, which means that exhaust gases have reached the speed of sound[1]. Limit velocity equation then is

$$V_9|_{max} = \sqrt{\gamma_g R_g T_9} \tag{3.2}$$

Where R_g is the air gas constant, γ_g is the relation of specific heat constants of air and T_9 is the air temperature in the point where speed of sound is calculated (downstream of the engine in this case). In this equation it has been assumed that $P_0 = P_9 = P_8$, reaching it by adapting the nozzle, so there is no direct pressure contribution to thrust. Assuming the whole process is isentropic the following relation give us the value of T_9 as a function of T_0 (ambient temperature) and the flight Mach number M_0. It has been calculated just applying ideal thermodynamic equations

$$T_0\left(1+\frac{\gamma_g-1}{2}M_0^2\right)\pi_f^{\frac{\gamma_g-1}{\gamma_g}} = T_{2t}\pi_f^{\frac{\gamma_g-1}{\gamma_g}} = T_{3t} = \left(1+\frac{\gamma_g-1}{2}M_9^2\right)T_9 = \left(1+\frac{\gamma_g-1}{2}\right)T_9 \tag{3.3}$$

Where π_f is the pressure ratio of the fan(quotient of the pressure after and before the fan), T_{2t} and T_{3t} are the stagnant temperature of the air before and after the fan respectively, M_9 and M_0 are the Mach number (quotient between velocity and the speed of sound) of the air upstream and

[1] It has been assumed that the nozzle is adapted so $P_8 = P_9 = P_0$, in this case $V_8 = V_9$ and also $T_8 = T_9$, **(Garcia 2007)**

downstream of the engine respectively, so as it has been said, when maximum thrust is provided $M_9 = 1$. Mixing the two last equations it is easy to reach the following expression

$$V_9|_{max} = \sqrt{\gamma_g R_g T_0 \frac{\left(1+\frac{\gamma_g-1}{2}M_0^2\right)\pi_f^{\frac{\gamma_g-1}{\gamma_g}}}{\left(1+\frac{\gamma_g-1}{2}\right)}} \tag{3.4}$$

This is a function that relates exhaust speed with environmental known variables and π_f (which is not known yet), so it seems it is necessary to add more equations in order to find the actual value of the exhaust gases velocity.

Now, considering the energy equation applied to the airflow per unit of mass, using the airplane as a reference system

$$\frac{V_9^2}{2} - \frac{V_0^2}{2} = \tau_f \tag{3.5}$$

Where τ_f is the specific power given to the air, coming from the fan. This easily lead us to

$$V_9 = \sqrt{V_0^2 + 2\tau_f} \tag{3.6}$$

If now it is considered the fan (which is an axial compressor) efficiency equation

$$\eta_f = \frac{c_p T_{2t}(\pi_f^{\frac{\gamma_g-1}{\gamma_g}} - 1)}{\tau_f} \tag{3.7}$$

Where η_f is the fan efficiency which will be considered equal to unity (due to ideal hypothesis) and c_p is be the specific heat constant of the air.

If (3.6) and (3.7) are mixed, considering $\eta_f = 1$ it finally appears

$$V_9 = \sqrt{V_0^2 + 2c_p T_{2t}\left(\pi_f^{\frac{\gamma_g-1}{\gamma_g}} - 1\right)} = \sqrt{V_0^2 + 2c_p\left(1+\frac{\gamma_g-1}{2}M_0^2\right)T_0\left(\pi_f^{\frac{\gamma_g-1}{\gamma_g}} - 1\right)} \tag{3.8}$$

Where stagnation temperature has been converted into conventional temperature using thermodynamic equations, being M_0 the flight Mach number (obviously equal to the air velocity upstream).
If it is considered as it has been said that V_9 has a superior limit, the speed of sound, given by the

equation (3.4), and if it is also known (3.8), it can be found the upper limit of the fan pressure ratio

$$\pi_f|_{max} = \left(\frac{\frac{2c_p}{\gamma_g R_g} - \frac{M_0^2}{1-\frac{\gamma_g-1}{2}M_0^2}}{\frac{2c_p}{\gamma_g R_g} - \frac{1}{1-\frac{\gamma_g-1}{2}}} \right)^{\frac{\gamma_g}{\gamma_g-1}} \tag{3.9}$$

This expression can be simplified knowing that, for example, $\frac{2c_p}{\gamma_g R_g} = \frac{2}{\gamma_g-1}$. Doing some algebra it is reached

$$\pi_f|_{max} = \left(\frac{1+\gamma_g}{2+(\gamma_g-1)M_0^2} \right)^{\frac{\gamma_g}{\gamma_g-1}} \tag{3.10}$$

This is the maximum pressure ratio the fan can provide before making the engine work in critical conditions. It is important to mention that, in first approximation (considering γ_g constant, which is not), it does not depend on height, only on speed.

It is crucial to understand that this value is the maximum pressure ratio the fan can provide before critical conditions, but in general it will be a degree of freedom, consequence of providing more or less power to the engine. Effectively, if the equation (3.7) is watched closely, this conclusion can be deduced from there. To set a value of the previous equation, working at zero speed, $M_0 = 0$, it leads to $\pi_f|_{max} = 1.9$

Because the pressure ratio has been calculated, the exhaust gases velocity can be finally deduced. Combining (3.4) and (3.10) there is

$$V_9|_{max} = \sqrt{\gamma_g R_g T_0 \frac{\left(1+\frac{\gamma_g-1}{2}M_0^2\right)\left(\frac{1+\gamma_g}{2+(\gamma_g-1)M_0^2}\right)}{\left(1+\frac{\gamma_g-1}{2}\right)}} = \sqrt{\gamma_g R_g T_0} \tag{3.11}$$

It is not a coincidence that the exhaust gases velocity is the same as the speed of sound upstream of the engine. Effectively in the whole process air entropy has not been increased due to ideal hypothesis. This means the air has not been heated and all the energy that has been given to it has been directed to increase its kinetic energy. This could have been foretold in (3.5).

It is not sufficient with calculating the exhaust gases velocity, it is also necessary to know the airflow in order to calculate thrust (see (3.1)). Now to determine the maximum thrust, and specially the quotient of thrusts between cruise range and take off $\frac{T_{CR}}{T_{TO}}$ (which is very important to the preliminary design) it is necessary to study the airflow, G. Again it will be considered critical conditions, because the importance of the upper limit to thrust.

Mass flow under critical conditions in the nozzle is **(Garcia 2007)**

$$G|_{max} = f(\gamma_g)\frac{P_{3t}A_8}{\sqrt{R_g T_{3t}}} \tag{3.12}$$

With $f(\gamma_g) = \sqrt{\gamma_g}\left(\frac{2}{\gamma_g+1}\right)^{\frac{\gamma_g+1}{2(\gamma_g-1)}}$, where P_{3t} is the stagnant pressure after the fan, and A_8 is the outlet engine area.

Knowing from ideal thermodynamics that

$$P_{3t} = P_0\left(1+\frac{\gamma_g-1}{2}M_0^2\right)^{\frac{\gamma_g}{\gamma_g-1}}\pi_f \tag{3.13}$$

and also looking at the left part of (3.3) finally airflow is deduced

$$G|_{max} = f(\gamma_g)\frac{P_0 A_8}{\sqrt{R_g T_0}}\left(\pi_f|_{max}\right)^{\frac{\gamma_g+1}{2\gamma_g}}\left(1+\frac{\gamma_g-1}{2}M_0^2\right)^{\frac{\gamma_g+1}{2(\gamma_g-1)}} \tag{3.14}$$

Now the maximum thrust of the engine can be calculated knowing the contour conditions (height, speed, temperature...) and also knowing how big the engine is (exhaust area) by combining equations (3.1), (3.10), (3.11) and (3.14) as following

$$T|_{max} = f(\gamma_g)\frac{P_0 A_8}{\sqrt{R_g T_0}}\left(\frac{1+\gamma_g}{2+(\gamma_g-1)M_0^2}\right)^{\frac{\gamma_g+1}{2(\gamma_g-1)}}\left(1+\frac{\gamma_g-1}{2}M_0^2\right)^{\frac{\gamma_g+1}{2(\gamma_g-1)}}\sqrt{\gamma_g R_g T_0}(1-M_0) \tag{3.15}$$

Introducing $f(\gamma_g)$ it can be sharply simplified to

$$T|_{max} = \gamma_g P_0 A_8(1-M_0) \tag{3.16}$$

It is important to remember that this is a value that represents the maximum thrust the engine can give, but in general thrust will be a degree of freedom depending on the amount of energy provided to air.

Looking at the equation it can be set the following conclusions:

- Increasing Mach numbers make maximum thrust to decrease, because margin to increase air velocity to speed of sound decreases, until, eventually, it is reached $M_0 = 1$ and therefore there is no remaining thrust.
- Maximum thrust increases with the size of the engine, given by A_8.

- Maximum thrust increases with the ambient pressure, due to the increment the amount of accelerated air mass.
- It also increases with the air constant γ_g, because as big it is, as high the speed of sound is (see equation (3.2)), and then there is more margin to increase the air velocity.

3.2.2 Power Calculation

Thrust has already been calculated. This was necessary in order to be aware of the engine limits at different altitudes and velocities. However, power is more important because it gives information about the energy that flying will consume, so it will make possible to calculate range and endurance.

The power that is necessary to fly is the power needed to cope with aerodynamic drag, given by the following equation

$$P_{flight} = TV \tag{3.17}$$

Where V is flight velocity. Though, there are loses in the process of flying. When the engine expels air backwards, it is providing thrust to the airplane, and so power to fly, but it is also giving kinetic energy to the airflow that abandons the engine. This can be measured defining the propulsive efficiency as

$$\eta_p = \frac{P_{flight}}{P_{flight} + P_{airflow}} = \frac{G(V_9 - V_0)V_0}{G(V_9 - V_0)V_0 + G\frac{(V_9 - V_0)^2}{2}} = \frac{2}{\frac{V_9}{V_0} + 1} \tag{3.18}$$

Where, as it can be seen, the propulsive efficiency increases if the quotient $\frac{V_9}{V_0}$ becomes smaller. Though, this has a limit, because if it reaches unity it means there is no thrust left to make the flight possible, as it can be seen in equation (3.1). It is important to mention that in this efficiency should also be introduced the thermal energy provided to the air flow coming from aerodynamic friction, but it has been considered ideal thermodynamics so that part has been implicitly neglected.

In case the engine is working at full thrust (V_9 equal to the speed of sound) then

$$\eta_p = \frac{2M_0}{1 + M_0} \tag{3.19}$$

Taking into account this new efficiency it can be said

$$P_{fan} = \frac{P_{flight}}{\eta_p} \tag{3.20}$$

Where P_{fan} is the power that receives the fan. There is one last intermediary between the source of energy and the power provided to the fan, and that is the electric motor, which is not perfect and will have also an efficiency η_m (will be considered constant), finally leading to

$$P_{bat} = \frac{P_{flight}}{\eta_m \eta_p} \tag{3.21}$$

Where P_{bat} is the power provided by the batteries. From this equation it can be seen the difference between a jet, a turboprop and a ducted fan:

In a conventional jet the energy consumption is related with T_{flight} with a constant, so it can be colloquially averred "you pay for thrust".

In the turboprop the energy consumption is related with P_{flight} with a constant, so in this case it would be "you pay for power".

In a ducted fan, due to variations in η_p with velocity, it cannot be said neither one nor the other. Though some similarity to one or the other can be recognised at different velocities, being similar to turbofan when flying at low speeds (low η_p), and similar to turboprop when flying at high speeds (high η_p).

3.3 Breguet Equations of a Battery Powered Airplane

Breguet equations are traditionally those equations that define range and endurance of a fuel powered airplane. In those equations is taken into account the fact that weight varies during flight due to fuel consumption.

In the case of a battery powered airplane it will be much easier to find those equations, because the aircraft weight will not change. In this section, because it is going to be studied the cruise part of the flight, the following hypothesis will be assumed:

- Straight line flight
- Steady and horizontal flight
- Zero angle of attack of thrust
- Zero roll angle

If the equilibrium of forces is set

$$T = D \tag{3.22}$$

$$L = W \tag{3.23}$$

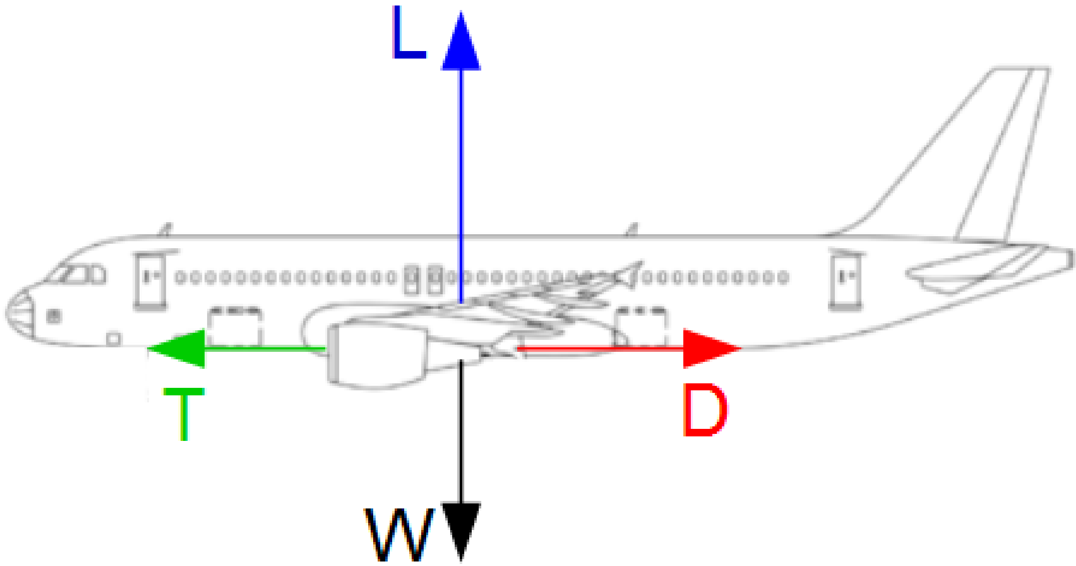

Figure 3.2 Scheme of forces in an airplane flying in cruise mode, taken from **Scavini (2011b)** and modified.

And defining aerodynamic efficiency, E as it follows

$$E = \frac{L}{D} \tag{3.24}$$

Then the following equation can be deduced

$$T = \frac{W}{E} \tag{3.25}$$

Now using this equation, (3.17) and (3.21) then

$$P_{bat}\eta_p\eta_m = \frac{WV}{E} \tag{3.26}$$

Now in order to calculate range and endurance (designated by letters R and t respectively), as it is done when deducing conventional Breguet equations, the following integrals are set

$$R = \int_{t_0}^{t_f} V dt \tag{3.27}$$

$$t = \int_{t_0}^{t_f} dt \tag{3.28}$$

Which using (3.26) will turn into

$$R = \int_{t_0}^{t_f} \frac{EP_{bat}\eta_p\eta_m}{W} dt = \int_{En_0}^{En_f} -\frac{E\eta_p\eta_m}{W} dEn = \int_{En_f}^{En_0} \frac{E\eta_p\eta_m}{W} dEn = \frac{E\eta_p\eta_m}{W}(En_0 - En_f) \tag{3.29}$$

$$t = \int_{t_0}^{t_f} dt = \int_{En_0}^{En_f} \frac{-dEn}{P_{bat}} = \int_{En_0}^{En_f} -\frac{E\eta_p\eta_m}{WV} dEn = \int_{En_f}^{En_0} \frac{E\eta_p\eta_m}{WV} dEn = \frac{E\eta_p\eta_m}{WV}(En_0 - En_f) \tag{3.30}$$

Where En is the remaining energy in the batteries. It is important to comment these expressions, specially the first one, which is related to range and will inform about the possibilities of the airplane. These equations could be simplified assuming $En_f = 0$, but because they are only valid in cruise stage, it is necessary to leave some remaining energy in the aircraft in order to descend and land.

As it can be seen, range increases with aerodynamic efficiency, energy stored in batteries, propulsive efficiency and electric motor efficiency, and decreases with weight.

Though, this is not that simple because these variables are related between each other. In order to set a deeper view in how can be range maximized here are the main relations between variables:

- The energy stored in batteries, $(En_0 - En_f)$ is related with weight W due to specific energy of batteries. Effectively batteries will be a major part of the aircraft weight
- The energy stored in batteries, $(En_0 - En_f)$ is also related with aerodynamic efficiency E due to energy density in batteries. Because batteries take much more space than fuel, it is likely that the fuselage will be lengthened in order to accommodate a part of the batteries (bigger wings would also be necessary in that case). This could cause a difference in aerodynamic efficiency due to different lift and drag.
- Propulsive efficiency η_p will we related with weight W. As it has been said before, η_p is higher when exhaust gases velocity and flight velocity are closer, but this leads to a poorer thrust which might not be able to satisfy equation (3.25).

Anyway, there is room for a very basic analysis in order to be concious of the possibilities of this kind of airplane, and also, to discover where is advisable to fly in order to maximize range, which will be a mayor challenge, as it will be seen.

Elemental Design: Number of Batteries vs Range

A very basic analysis of the possibilities of batteries in the aeronautical world can be performed. In order to simplify the equations it is going to be assumed that aerodynamic efficiency is independent of everything else and constant. It has been stated the opposite just a few paragraphs before, but this approximation is done just to get some rough numbers, in a further study these variations will also be considered. Another strong approximation will be neglecting other parts of the flight, assuming then that all the energy is consumed in cruise mode, this will also be addressed deeper in the a further study.

In that case, if it is known that

$$s_e = \frac{En}{m_{bat}} \tag{3.31}$$

Where s_e is the specific energy of batteries. Then introducing it into equation (3.29)

$$R = \frac{E\eta_p\eta_m s_e}{g}\left(\frac{W_{bat}}{W}\right) \tag{3.32}$$

Where range is clearly expressed as a function of the batteries share in the overall weight. This means that, in a very first approximation, range will not depend on the airplane size, but on the proportion of batteries it has. Of course it can be reasoned that bigger airplanes have less duplicities of systems than small ones, and the effect on weight of those systems will be lower, leaving a higher margin for loading batteries.

Looking at this equation it can be stated there is a natural limit for battery powered airplanes. If it is assumed that the whole airplane is made of batteries, $\left(\frac{W_{bat}}{W}\right) = 1$, then this ultimate range would be

$$R|_{ultimate} = \frac{E\eta_p\eta_m s_e}{g} \tag{3.33}$$

Using some values like $E = 17$, $\eta_p = 0.82$[2], $\eta_m = 0.98$**(ENSTROJ 2014)** and also considering a value of specific energy found in futuristic batteries like Li-S, $s_e = 1.8MJ/kg$ **(Song et al. 2013)** will lead us to a $R|_{ultimate} \approx 2500$ km which is not a great number taking into account that the whole airplane is made of batteries. If the proportion of batteries were the half, the range would halve. This imposes that battery powered airplanes are, at best, restricted to short range, where alternatives like train are becoming more and more competitive.

[2] M=0.7 aprox using ec. (3.19)

Fixed Design

Once design is fixed it is important to be aware of how is it better to fly, this means discovering at which speed and heigh range would be maximized. If the design of the aircraft is already decided, looking at the equation (3.29) the only variables which are not fixed are η_p and W (because payload will be variable).

To maximize η_p it is necessary that V_9 and V_0 were as close as possible. Because thrust decreases with that difference (see equation (3.1)) it is necessary to increase the air flow guzzled by the engine in order to maintain flight, as seen in equation (3.25). In order to achieve that it will be necessary to fly as low as possible (in the limit, at sea level). This sets a sharp contrast between the traditional jet engine, which has its maximum efficiency at high altitudes.

Because reducing $(V_9 - V_0)$ will reduce power, soon or later it will be reached a point were this can no longer be shorten in order to maintain cruise flight. If this difference is constant, the way of maximizing the quotient $\frac{V_9}{V_0}$ (necessary to improve η_p, see equation (3.7)) is increasing flight speed, V_0.

In conclusion, theoretically, the best way of flying is at sea level and at maximum speed. This also would improve endurance, making the flight shorter. Though, in this brief analysis it has only been taken into account cruise phase. In reality, landing will set a very restrictive requirement, imposing the airplane to have big wings, and then it will be necessary to fly with lower air densities (higher) in order to reduce the excessive interaction between the big wings and the air, achieving a better E.

It is also necessary to do a simple study of how payload affects range, generating then the payload-range diagram. If in equation (3.29) weight is separated then

$$R = \frac{E\eta_p\eta_m\Delta En}{W_{OEW} + W_{PL}} = \frac{E\eta_p\eta_m s_e}{g}\left(\frac{W_{bat}}{W_{OEW} + W_{PL}}\right) \tag{3.34}$$

Where ΔEn is the difference of remaining energy in batteries along the cruise. This lead us to a Diagram like the following, composed only by two lines.

As it can be seen, the diagram is composed by two regions: one limited by physical space and structural resistance of the aircraft, which is the horizontal line, prevailing the limitation of maximum payload, and another one, where the effects of the equation (3.34) prevail, leading to a hyperbolic behaviour until eventually there is no payload on the aircraft.

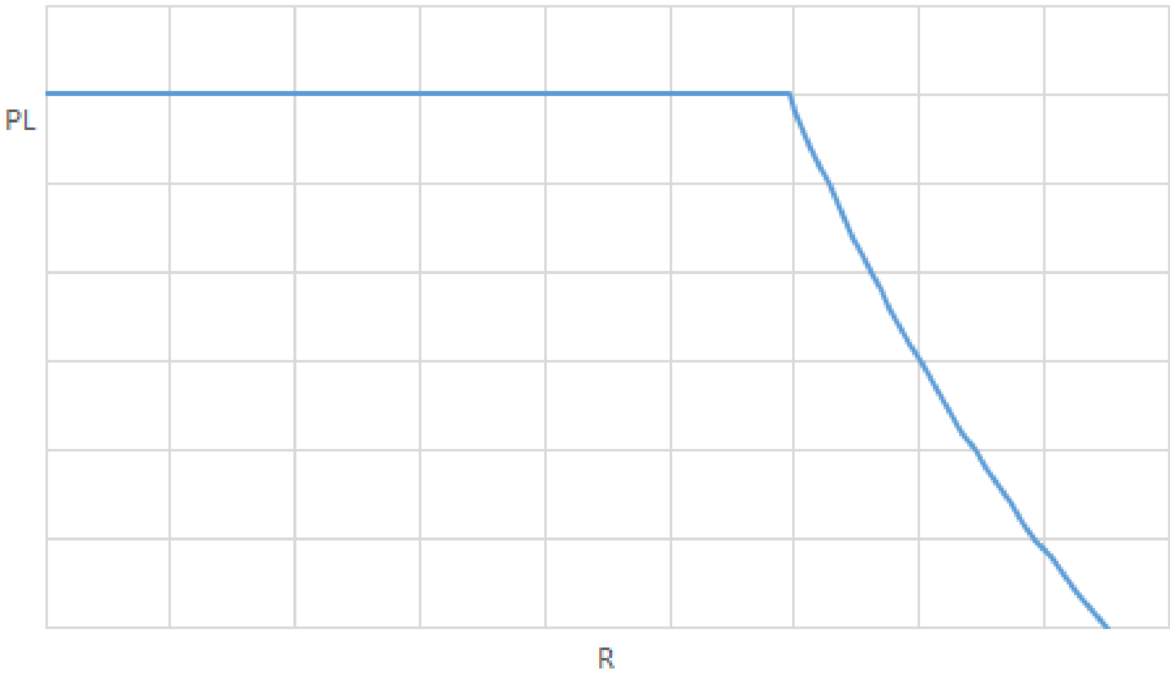

Figure 3.3 Payload-Range diagram in a battery powered airplane.

4 Aircraft Design

4.1 Introduction

Aircraft design is a discipline where, in the first place, the new aircraft is dimensioned in its very basic variables by looking at similar airplanes, and then, in the second place, a deeper study is made in order to integrate all the systems of the project into a single airplane.

The basic design charts involve two main variables. On the one hand wing loading, which is take off mass divided by wing area, and, on the other hand, dimensionless thrust, which is thrust divided by take off weight.

These two variables involve three realities related between them and will give us information about the four main forces in the airplane:

- Wing area, which will give us information about lift and drag forces
- Weight
- Thrust

It will be seen that each phase of the flight (take off, climb, cruise...) will impose its own requirements, and that will lead to a matching chart, where there will be a subspace where all requirements are fulfilled, and that will define a design point, meaning one concrete dimensionless thrust and one concrete wing loading. After that, from range and payload requirements, along with operative empty weight estimations, take off weight will be calculated, and in consequence, take off thrust and wing area will be deduced. At that point the preliminary design would be already finished.

It is important to mention that thrust is not always the variable associated to the propeller. Sometimes, this analysis is performed using power instead. The factor that makes us choose one or the other is the propeller; whether if it is defined by thrust (like jet engines) or defined by thrust (like turboprop engines). In this case, because as it has been explained in the previous chapter, the ducted fan is in the middle of these two kinds of behaviour, it is complicated to choose one or the other. Thrust will be the preferred one because it is better to keep the same framework as in the A320 in order to set a fair comparison.

It could happen that results are not possible, for example, because there is no space for an engine big enough to provide the necessary thrust. In that case requirements will be checked again, and perhaps modified in consequence.

4.2 Equations of the different Flight Phases

In this section, equations are going to be presented without showing them and their origin in detail. These equations are well known and if it is necessary to know more about them, specialized bibliography can be checked **(Scholz 2012)**. It is more than advisable to check the Appendix B, where basic equations of Aerodynamics are exposed. During this section it is assumed that the reader already knows them and possesses a basic knowledge of aerodynamics.

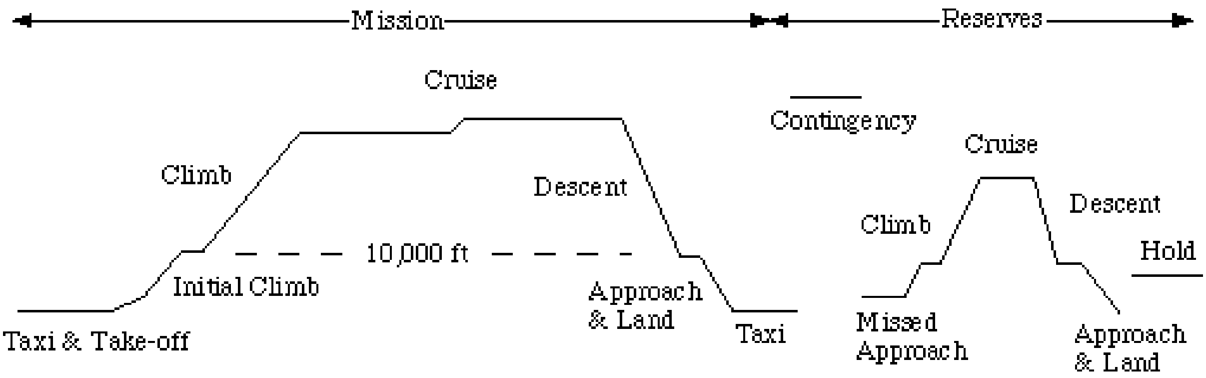

Figure 4.1 Typical flight profile whit its different flight phases.

4.2.1 Take-off

For the take-off, the energy equation is applied between the start and the lift-off moment, called take-off ground roll. If wind speed is neglected and it is considered that thrust is the mayor force in the process then

$$T_{TO} s_{TOG} = \frac{1}{2} m_{TO} V_{LOF}^2 \tag{4.1}$$

Where T_{TO} is the take-off thrust, s_{TOG} in the distance of take-off ground roll, m_{TO} is the take-off mass and V_{LOF} is the lift-off velocity. Lift-off velocity can be expressed by setting forces equilibrium in the lift-off moment

$$V_{LOF} = \sqrt{\frac{2 g m_{TO}}{\rho S_W C_{L,LOF}}} \tag{4.2}$$

Where S_W is the wing area and $C_{L,LOF}$ is the lift coefficient in lift-off configuration.

If the two equations are combined it leads to

$$\frac{T_{TO}/(m_{MTO} g)}{m_{MTO}/S_W} = \frac{g}{C_{L,LOF} \rho s_{TOG}} \tag{4.3}$$

It can be used a constant to set a relation between s_{TOG} and s_{TOFL}, which is the take-off field length. In that constant it can also be involved gravity and density at sea level, leading to

$$\frac{T_{TO}/(m_{MTO}g)}{m_{MTO}/S_W} = \frac{k_{TO}}{C_{L,LOF}\sigma s_{TOG}} \tag{4.4}$$

Where σ is the quotient between density at a determinate altitude and density at sea level, and $k_{TO} = 2.34 m^3/kg$.

As it can be seen, this equation sets a limitation between the two main variables, being the equation that sets it a linear relation between them.

4.2.2 2nd Segment Climb with Engine Failure

Second newton law gives us for this climbing phase, taking into account that the climb angle, γ, is small

$$T = D + mg\sin\gamma \tag{4.5}$$

$$L = mg\cos\gamma \approx mg \tag{4.6}$$

Dividing the first equation by the second one, considering that thrust is approximately equal to the take-off thrust, and setting an engine failure we know

$$\frac{T_{TO}}{m_{TO}g} = \left(\frac{n_E}{n_E - 1}\right)\left(\frac{1}{E} + \sin\gamma\right) \tag{4.7}$$

Where the climb angle is given by regulations.

4.2.3 Cruise Phase

The analysis of this phase is slightly different than the traditional one, seen in **Scholz (2012)**. In this case, as it could have be seen in the analysis of the equation (3.34) there is a coupling between variables that makes impossible to impose an aerodynamic efficiency taken from flight mechanics theory, in this case Breget equations are different, and so the nature of the aircraft itself.

The parabolic polar is usually described as

$$C_D = C_{D0} + \frac{C_L^2}{\pi A \varphi} \approx C_{D0} + \frac{C_L^2}{\pi A e} \tag{4.8}$$

Where A is the aspect ratio, φ is the aerodynamic efficiency factor and e is the Oswald factor. C_D is the drag coefficient, C_{D0} is the zero-lift drag coefficient, and C_L is the lift coefficient. The Oswald factor only takes into account the variation of drag coming from a variation in potential induced drag, and does nor take into account the variation of the friction part with the angle of attack as the aerodynamic efficiency factor does. In this approximation this effect has been neglected.

Now in cruise phase, being aware of the equilibrium of forces, it can be said

$$\frac{1}{E} = \frac{T}{W} = \frac{D}{L} = \frac{C_{D0}}{C_L} + \frac{C_L}{\pi A e} \tag{4.9}$$

From the vertical equilibrium of forces it can also be set

$$C_L = \frac{2gm/S_w}{\rho V^2} \tag{4.10}$$

Combining the two equations, knowing that $m_{TO}g = W$ in a battery powered airplane, and doing some algebra easily leads to

$$\frac{1}{E} = \frac{T}{m_{TO}g} = \left(\frac{C_{D0}\rho V^2/g}{2m_{TO}/S_W} + \frac{2g(m_{TO}/S_w)}{\pi A e \rho V^2} \right) \tag{4.11}$$

Which finally turns into

$$\frac{T_{TO}}{m_{TO}g} = \frac{T_{TO}}{T} \left(\frac{C_{D0}\rho V^2/g}{2m_{TO}/S_W} + \frac{2g(m_{TO}/S_w)}{\pi A e \rho V^2} \right) \tag{4.12}$$

Where the quotient $\frac{T_{TO}}{T}$ can be easily deduced from equation (3.16). The rest of variables are known, or come from requirements (altitude, velocity...) or come from the state of the art.

4.2.4 Climb Rate during Missed Approach

The reasoning is exactly the same than seen in subsection 4.2.2, the only aspect that changes is the weight (also the climb angle that allows the regulation), because now we are talking about a missed landing, so landing weight operates now

$$\frac{T_{TO}}{m_{TO}g} = \left(\frac{n_E}{n_E - 1} \right) \left(\frac{1}{E} + \sin\gamma \right) \frac{m_{ML}}{m_{MTO}} \tag{4.13}$$

This limitation is usually less demanding than the second segment climb, but for a battery powered airplane it will be exactly the same.

4.2.5 Landing

From **Loftin (1980)** it can be taken an empiric relation between approach velocity and landing field length

$$V_{APP} = k_{APP}\sqrt{s_{LFL}} \tag{4.14}$$

With $K_{APP} = 1.70\sqrt{m/s^2}$. Now setting vertical equilibrium of forces in landing phase

$$\frac{m_{ML}}{S_W} = \frac{\sigma\rho_0 V_{APP}^2}{2g} C_{L,max,L} \tag{4.15}$$

Which introducing the empiric relation finally lead us to

$$\frac{m_{MTO}}{S_W} = \frac{m_{MTO}}{m_{ML}} k_L \sigma C_{L,max,L} s_{LFL} \tag{4.16}$$

Where k_L is a constant that involves constants like gravity, density, or K_{APP}. Its value is $k_L = 0.107 kg/m^3$

4.3 Matching Chart

As it has been said, all the equations expressed in the previous section lead to a chart where the two optimization variables ($\frac{T_{TO}}{m_{TO}g}$ and $\frac{m_{MTO}}{S_W}$) are chosen respecting the limitations set by them. The matching chart then looks like the following.

Where the first priority is to have the lowest dimensionless thrust, and the second one is to have the biggest wing loading possible. Following these rules is easy to set a design point, which will define our aircraft.

4.4 Take-Off Mass

From the matching chart it is clear that, if take-off mass is known, then wing area and take-off thrust are easily deduced.

To know then the take-off mass, it is crucial to have an estimation of the operative empty mass divided by the maximum take of weight, $\left(\frac{m_{OE}}{m_{MTO}}\right)$. This estimation can be taken from **Markwardt (1998)**, for example, but in this work it has been estimated by estimating the weight of each part of the airplane, using empiric relations implemented in OPerA, the tool used in the HAW. This leads equations to be slightly different in this tool, but because the general con-

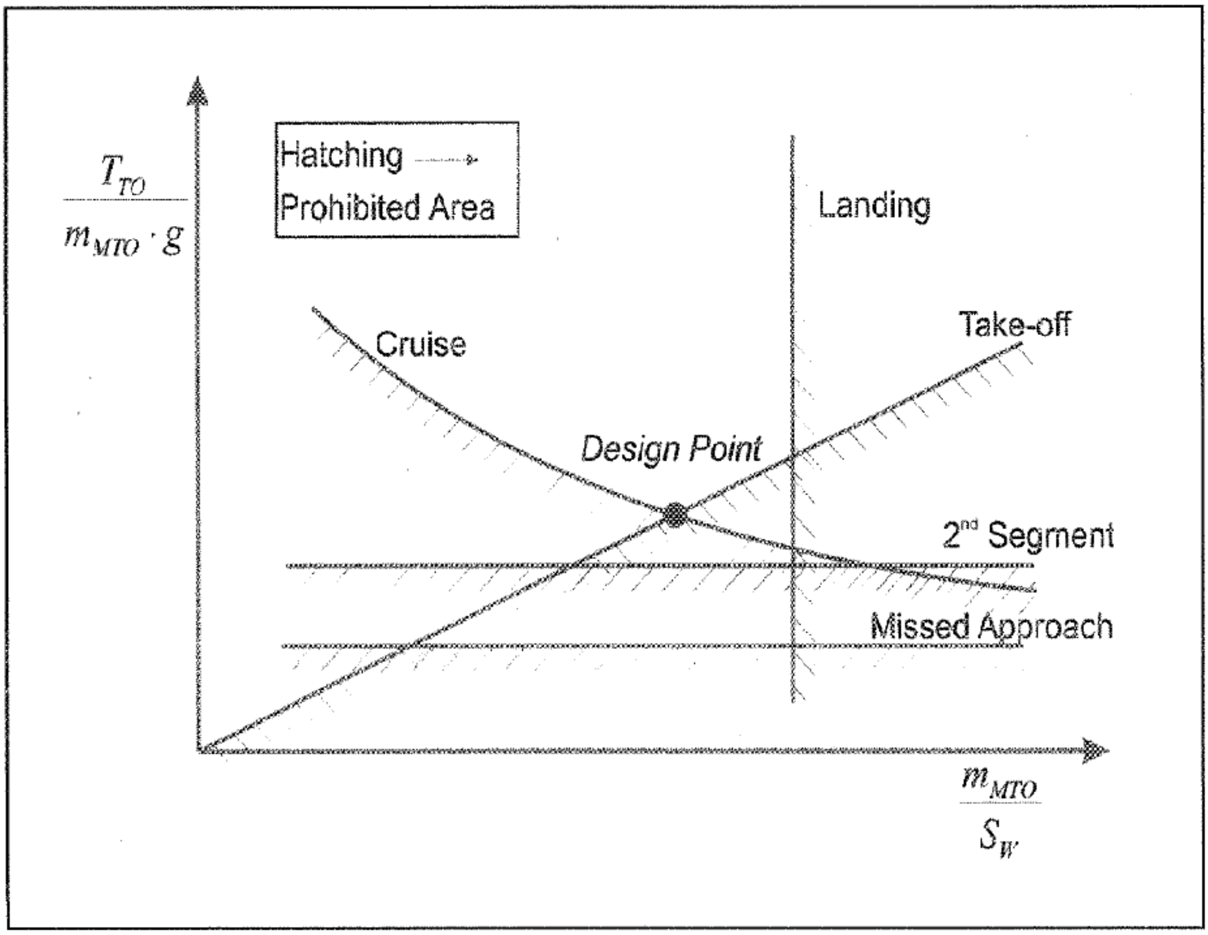

Figure 4.2 Hypothetical matching chart taken from **Scholz (2012)**.

ceptual process of Aircraft Design is being addressed here, that information is exposed in the Appendix C.

On the other hand, battery fraction given by equation (3.32) will be also necessary to deduce maximum take-off weight. It will be known because range will be a requirement, and the rest of parameters will be estimated or deduced (equations (3.19) and (4.11)).

Once these two weight fractions variables are known, also knowing the payload (from the requirements), maximum take-off weight can be deduced as

$$m_{TO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}} \tag{4.17}$$

4.5 Take-off Thrust and Wing Area

Now finally take-off Thrust and Wing Area can be deduced easily given the point in the matching chart as

$$T_{TO} = m_{TO}g\left(\frac{T_{TO}}{m_{TO}g}\right) \tag{4.18}$$

$$S_W = m_{MTO}/\left(\frac{m_{MTO}}{S_W}\right) \tag{4.19}$$

At this point, the preliminary aircraft design would be already finished. After that, It would be necessary to materialize that design in a detailed design.

5 Calculations

5.1 Introduction

In this chapter there will be a brief explanation of how calculations where done.

In the first part the very basic principles of OPerA tool will be explained, and it will be seen how deep this tool calculates the possibilities of an hypothetical airplane.

In the second part the implemented changes in the tool in order to adapt it to battery powered airplane will be explained. Some of them have already been described in chapter 3, but some of the data, such as electricity price in the wholesale market(necessary to charge the batteries) or the engine weight estimations must be also clarified.

In the third part, requirements for our modified A320 will be discussed.

Finally, in the fourth part a list of the main hypothesis will be stated, so things will be clear before the results are shown.

5.2 Explanation of the Program OPerA

OPerA tool is a program developed in the Hamburg University of Applied Sciences (HAW) that allows to perform a preliminary design with a considerable level of precision. It is programmed in Visual Basic, comprehending all parts of aircraft design, specially giving great estimations in Operative Empty Weight and in Lift-to-Weight ratio.

The program inputs are the requirements of the airplane, such as payload, range, take-off field length, etc. The output is the whole design of the airplane, and also the direct operative cost (DOC), which will be the variable to optimize.

It is important to say that in the end, the program sets a very coupled system of equations that is solved using an algorithm. Because of that, the reader can feel that, according to the description, the program does not follow a straight line and there is always a feedback from somewhere.

5.2.1 Aerodynamics

The program calculates zero lift drag from estimating wetted areas of the airplane (knowing the necessity of space inside of the airplane because of the number of passengers requirement), calculating the corresponding friction coefficient and then scaling every part of the airplane drag with different interference factors that come from experience.

On the other hand, for calculating lift the program calculates the airplane Oswald factor. In order to do that it calculates the theoretical one given the wing taper ratio and wing aspect ratio, and then it is multiplied by a compressibility factor and a statistical empiric value.

At this point, the polar of the airplane is already calculated.

5.2.2 Weight Estimations

For calculating weight the airplane is divided in different parts: landing gear, engines, horizontal tail, vertical tail, wings, fuselage, systems and operators items.

Inside of each part there is also a whole set of elements whose weight is calculated or estimated based on empiric relations or official Airbus data.

5.2.3 Matching Chart

Aerodynamic forces, weight, and Thrust (from section 3.2.1) are now known. The matching chart already explained in the previous chapter then is used to match these inputs in a design point, so finally wings size and Thrust is calculated.

At this point the technical part is fully known.

5.2.4 Direct Operative Cost

From this point DOC is calculated by using two different methods: AEA 1989 method and the Technical University of Berlin (TUB) method.

Each method divides cost in different aspects such as depreciation, interests, insurance, fuel, maintenance, crew and fees. Finally each cost is calculated according to each method, leading us to the most important value that must be optimized, because it will inform us of the economical feasibility of the airplane.

5.3 Explanation of the Equations and Data Implemented

Other changes beyond shown in chapter 3 will be explained here. All of them can be divided in four parts: Engine Weight, prices, Non-cruise energy consumption and Airplane lengthening.

5.3.1 Engine Weight

Because the basic design of the engine changes, as shown in chapter 3 it is necessary a new estimation of weight. In order to do that, the engine will be divided in two parts: nacelle and electric motor.

Nacelle weight will be estimated by using empirical equations from **Torenbeek (1982)**, which are already integrated in OPerA. On the other hand, to estimate the weight of the engine a very simple linear relation will be set. Knowing the power-to-weight ratio of an electric motor, it will be extrapolated to any possible motor size. The number used will be 8.4 kW/kg **(ENSTROJ 2014)**.

It is important to mention that this is a conservative estimation, because there is a clear trend in data that shows that power-to-weight ratio goes bigger with the size of the motor, and the value that has been taken is coming from a 100KW motor, which is quite smaller than the motors that will be considered here.

5.3.2 Prices

For the prices, there are some variables that will be taken from different forecasts as true. Battery price is predicted to be 350$/Kwh by 2020 **(Dinger et al. 2010)** and it will also be considered that by that year electricity in the wholesale market will cost 60$/Mwh **(Askja 2014)**.

Other prices, like oil price (it will be necessary in order to compare costs), will be taken as a degree of freedom because its value is historically subject to big fluctuations **(Guo and Kliesen 2005)**.

5.3.3 Non-Cruise Equations

Normally for analysing the non-cruise phases there is an estimation of the percentage of fuel lost during each phase based on experience.

Now the analogue assumption will be assumed; those percentages in fuel that are consumed in those phases will be the percentages of energy stored in batteries consumed in the same phases. This is a good approximation for phases which are close to take-off, because in that point a fuel powered airplane still weighing the same. Though, in phases close to landing, such as descent, this will be an optimistic hypothesis, because fuel consumption in a fuel powered airplane will be lower due to the decrease of weight. Anyway, because it is being considered a short range airplane this assumption will not be far away from reality.

5.3.4 Battery Technology

When using battery technology values, it will be taken values from a futuristic kind of battery which has already shown results in the laboratory, so results will be exposed with rigour. This kind of battery will be the Lithium-Sulfur battery, whose values or specific energy and energy density are 1.8 MJ/kg and 1.26 MJ/l respectively.

This kind of battery is also now on the spot for the future of battery powered transport, so is likely that in the future a big investment will be put into this technology, leading it to industrial production **(White 2014)**.

Finally, it will be considered that the number of cycles this kind of battery will be able to stand is 1500 **(Song et al. 2013)**, after that they will be disposed.

5.3.5 Airplane lengthening

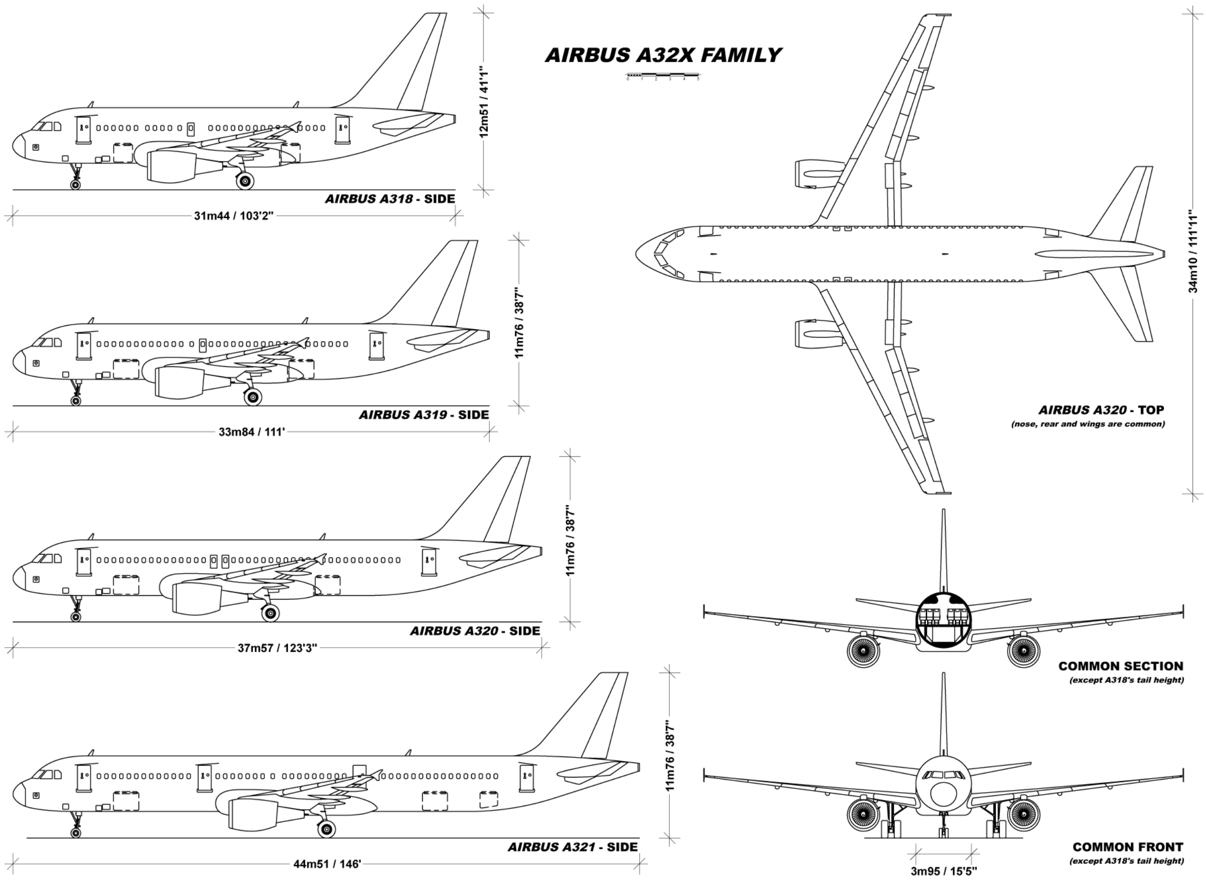

Figure 5.1 Airplane lengthening in the A320 family. Image taken from **(Scavini 2011a)**.

Because the energy density of the batteries could not be sufficient to accommodate the whole pack of batteries into the wings, it has been implemented in the program the possibility of lengthening the fuselage in order to get extra space to the batteries.

There is also a limit for this, because the airplane can not be lengthen eternally. The limit is reaching a slenderness of 12.5, which is the biggest value that can be found in commercial aircraft design, found in the B777 **(Tsang 2013)**.

5.4 Requirements

As it has been said, requirements are the input of the program. Initially the only requirements that initially will remain from the A320 are: payload and range. The rest of them will be optimized to achieve a minimum cost, DOC, with some boundaries given by the sector.

Because it is being considered a short range flight, Mach number will not be very important for the quality of the flight, so it will be optimized even if it seems a very basic variable.

Also take-off field length and take-off landing length will be set as the larger of the two, because it will be considered that the airport length will be the same for landing than take-off.

5.5 List of Hypothesis

In this section a list of the main hypothesis made for the calculations will be set, divided in optimistic and pessimistic.

Optimistic hypothesis:

- Corrosion, explosive events and safety issues neglected.
- Limit of power provided by batteries neglected, so they are seen as a deposit of energy where it can be extracted as it is needed.
- Energy consumption in flight phases different to cruise analogue to fuel powered airplanes.
- Stop over time (The time that takes to prepare the airplane for an extra flight once it arrives to an airport) will be the same as it is in the current A320.
- Ideal isentrophic ducted-fan engine.
- Cost associated with interests, insurance, maintenance, crew and fees equal to fuel powered airplanes.
- Futuristic battery properties and costs.
- Efficiency of recharging batteries equal to one.
- Influence of the magnetic field coming from the electric motor neglected.
- Not considered the replacement of batteries in design.

Pesimistic hypothesis:

- Limitation of space given by slenderness of 12.5, possibilities like adding a double bubble fuselage has not been considered.
- Power-to-weight ratio of the electric motor taken in a conservative way
- Electric motor efficiency taken from a smaller motor, 0.98. Usually efficiency improves with size **(ENSTROJ 2014)**

6 Results

6.1 Introduction

In this chapter results of the calculations will be shown. It is important to keep in mind the hypothesis mentioned in the previous chapter in order to ponder conclusions correctly.

In the first part of the chapter is going to be used real values of futuristic batteries (lithium-Sulfur). With this values It will be impossible to fulfil the requirements, so this case will be analysed in this way: How much range must be reduced to keep the same payload.

In the second part the following question will be answered: How good batteries need to become in order to be feasible in aircraft? This question will be answered in two mainstream points of view, one technical and another one economical. It will be set a border in batteries quality beyond which batteries are feasible in those aspects.

6.2 Batteries with Futuristic Real Values, Reduced Range Aircraft

As it has been said, it is impossible to fulfil A320 requirements with futuristic battery technology. Batteries are too heavy, and that leads the program to consider bigger landing gear and bigger engine, and because of this, extra energy is necessary so batteries become heavier, and this loop continues until the program breaks down. In order to dodge that, basic requirements will be changed by reducing range.

Summarizing, inputs introduced in the program to are:

Table 6.1 Inputs introduced to the program

PayLoad	20186	kg
Specific Energy	1.8	MJ/kg
Energy Density	1.26	MJ/L
Cost per unit of capacity	400	$/KWh
Electricity Price	0.06	$/KWh
Motor efficiency	0.98	
Cycles batteries can work	1500	

With these inputs the maximum range possible is 175 nautical miles, which is quite few. This means that the longest flight covered by this airplane would be something similar to Hamburg-Amsterdam.

In consequence, logistics of this airplane would be a big problem, because this distance is so short that would not allow an air company to fulfil market requirements satisfactorily, having to establish routes of connections different than the ideal ones because of the necessity of stopping every 175 nautical miles.

6.2.1 Flying Point; Ideal Altitude and Velocity

It is interesting to study where this airplane would fly and at which velocity in order to maximize its poor range. First, it is important to state the advantages and disadvantages (from maximum range point of view) of flying faster or higher. In order to do that, first of all it is important to mention that, because the airplane landing weight is very large, big wings will be necessary in order to satisfy landing requirements.

Flying faster leads to a larger propulsive efficiency, as shown in equation (3.19), but this also means it will be necessary a bigger and heavier engine to satisfy equation (3.16), there will also be lower maximum Lift-to-Weight ratio, E (due to compressibility effects), and because of the big wings dimensioned to landing, flying away from the optimum angle of attack, and so the optimum E.

Flying Higher leads to fly close to the optimum E, because the big wings have less interaction with air at a high altitude, but it also means to fly with a bigger and heavier engine in order to keep guzzling the same airflow.

As a result of the optimization, altitude and Mach number are $h = 4771$ m= 15654 ft and $M = 0.63$, so this airplane would fly slower than a commercial jet airplane and at a much lower altitude. It is fair to mention that, from this point of view, this airplane is more similar to turboprop airplanes than jets.

6.2.2 Airplane Mass and its Distribution

Because of the enormous weight of batteries, the airplane will be extremely heavy taking into account the payload carried: Its Take-off-Weight will be $W \approx 275$ tons which is quite heavier than a A350 (capable of carrying twice the A320 payload). Distribution of mass is shown in the following representation.

It can be observed the enormous share of batteries in the overall weight, this sets a sharp contrast between common short-range airplanes which have around 20% share of fuel.

From the figure it can be deduced that reducing payload will not extend range much more, because its share is minimum. It is clear then that the only way of improving range is reducing operative empty mass and, specially, improving battery technology.

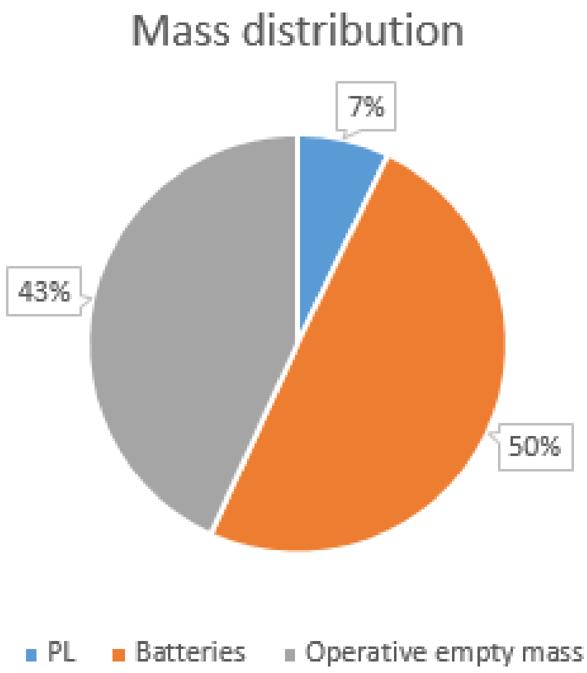

Figure 6.1 Mass distribution, it is compelling the measly share of payload in the overall weight.

Operative Empty Mass

It can be interesting to have a closer look to the operative empty mass so it can be observed how the airplane changes from a normal one. In order to do that properly, it will be presented a comparison between the original A320 and this battery powered A320.

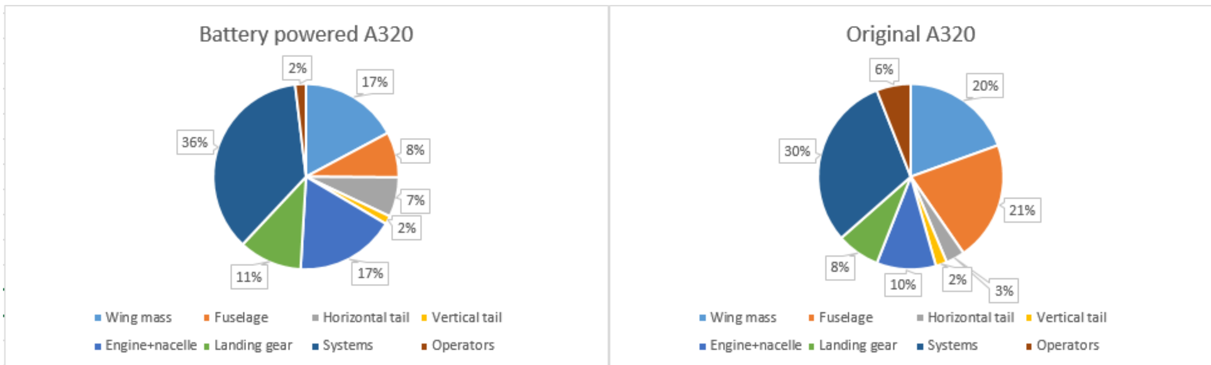

Figure 6.2 Operative empty mass distribution,comparison between the original A320 and the Battery powered one.

Operators(such as crew, containers or lubrication fluids) and Fuselage reduce sharply their share in the overall empty mass, because there is an increment of weight in other items so its participation gets diluted.

Wings, despite their growth, slightly reduce their share because of the big increment of other shares. In fact, the horizontal tail grows in order to provide stability to the airplane because of the growing wings.

But the main growth is detected in the mass of the systems, landing gear and engine. Systems grow because of the necessity of wiring and, in general, because of the mass increment. Landing gear becomes heavier because landing weight is now the same as take-off weight, so it is obvious that a bigger landing gear will be necessary to cope with this extra weight when landing. Finally, engine becomes heavier because the ducted fan has a poorer Weight-to-Thrust ratio, being necessary an enormous engine to provide an acceptable thrust.

Battery Mass

Battery mass can be divided in the different flight phases whose necessary energy is provided by it (cruise, climb, descent, taxi...) and also the different safety requirements (alternative airport, loiter...). If this is represented leads us to

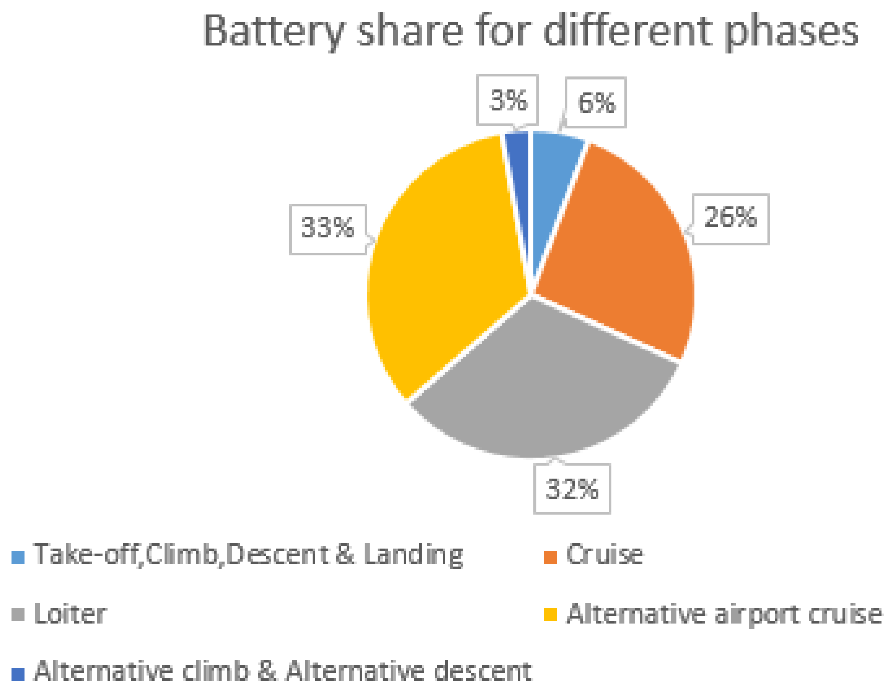

Figure 6.3 Battery distribution for different flight phases and safety requirements.

It can be seen that safety requirements take a enormous share in batteries. From a different point of view it could be said that batteries are so inefficient that they waste a huge capacity on satisfying safety requirements. If the safety requirements are removed, range could easily triple, leading to better possibilities in flying.

It is fair to mention that this diagram has been made assuming international flight rules, which are exposed in FAR part 121. If domestic flight rules are applied, alternative airport share would be smaller and loiter time share would be larger.

Payload-Range Diagram

The characteristic payload-range diagram of the designed airplane is the following. It obeys to the same algebraic relations than explained in section 3.3.

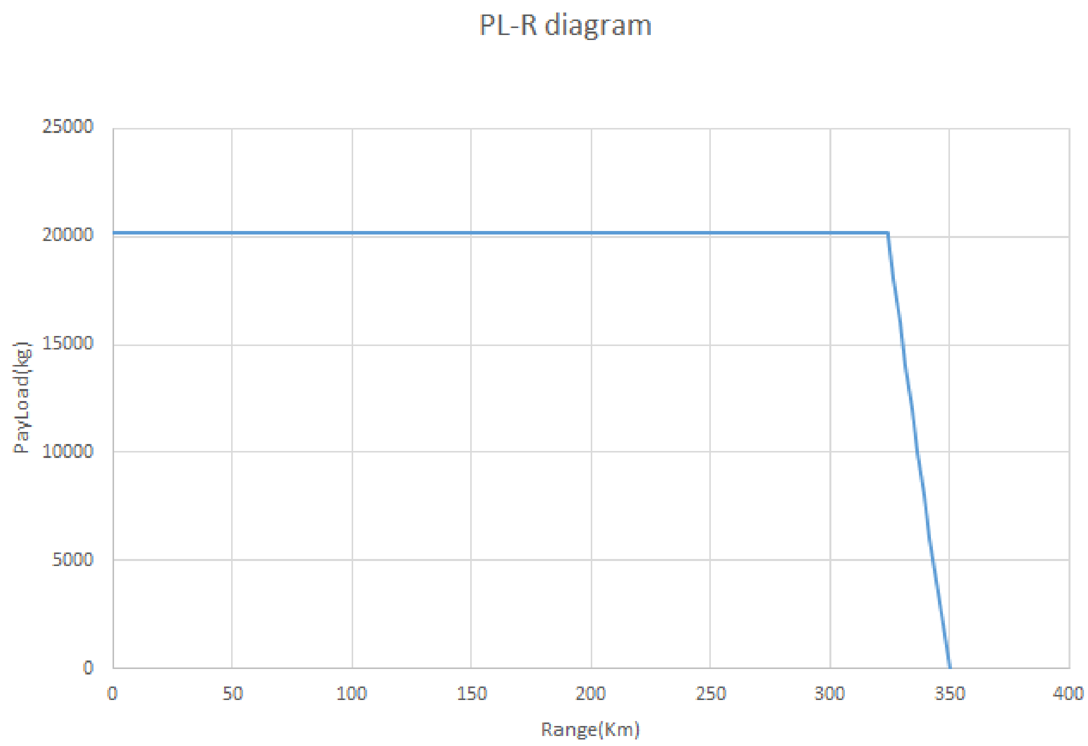

Figure 6.4 Payload range diagram for the designed battery powered airplane

Because payload represents a very small share in the overall weight, as it has been exposed previously, reducing it does not add too much range.

In consequence, there is no other way of improving range considerably than improving technology used in the aircraft (using lighter materials and lighter batteries).

6.2.3 Direct Operating Cost(DOC)

It is complicated to set a fair comparison in costs because of the extremely reduced range of the airplane. In consequence, cost will be exposed here but it is important to remember this issue.

Cost will be exposed as the price per ton carried per nautic mile, and because this units are independent from range, it can vaguely be set a comparison with the original A320, not forgetting the conceptual distance. In consequence, this will only give us a clue of how expensive would this airplane be, neglecting some items (exposed in the list of hypothesis, section 5.5).

There are several ways of calculating costs, in this text, as it has been mentioned before, calculations have been made using two different methods, the Association of European Airlines(AEA) method, 1989 and the Technical University of Berlin(TUB) method. The two methods shown give a very similar result, with enough precision for a preliminary design work as done here.

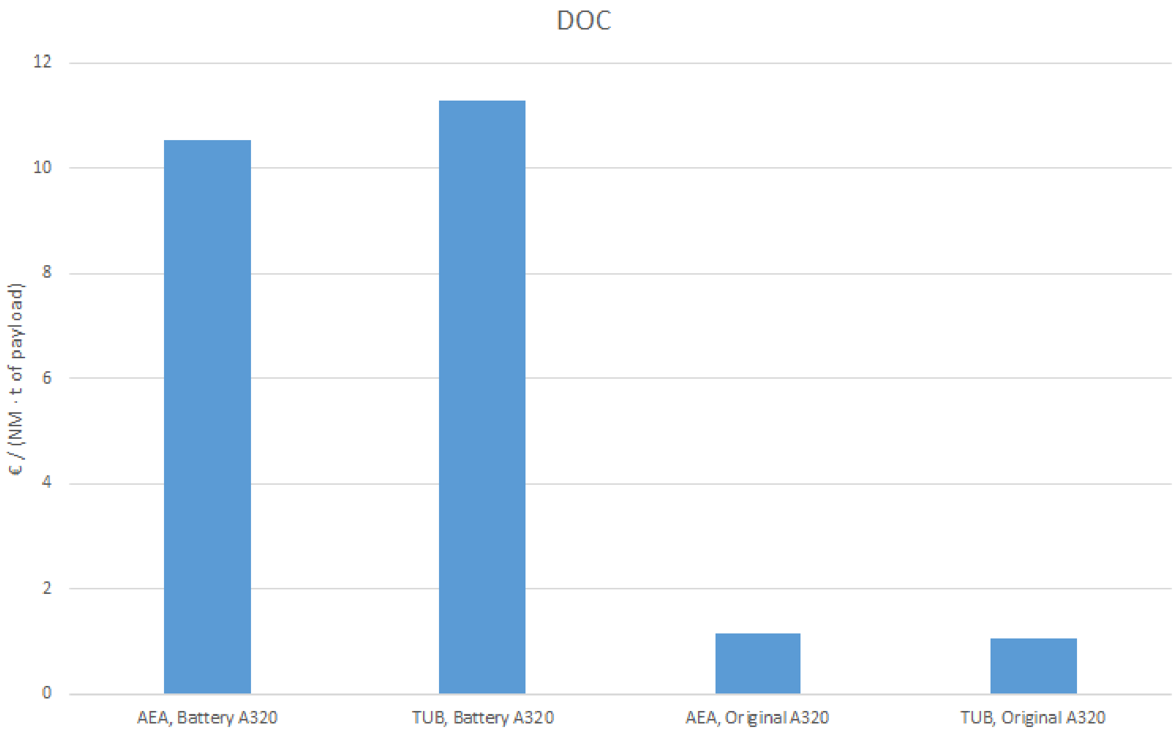

Figure 6.5 Comparison of costs between the designed battery-powered A320 and the original one, using two different methods.

To set an rough number, with all the considerations and hypothesis made, it would be necessary that oil became twenty times more expensive in order to have the same DOC. Of course this is not realistic, humanity would suffer probably the biggest economic crisis in all history, and for sure battery and electricity prices would be altered.

Looking inside of the costs of the battery powered airplane, the following chart is revealed.

It is fair to mention that the biggest share is taken by batteries, fees, depreciation and interests.

Batteries are then the main item whose cost must be reduced in order to make the airplane economically feasible. Also fees take a big share of the cost. This is because range is so low, making each flight so short, that the program assumes an enormous number of flights per year. This leads to an outstanding number of operations in airports and air navigation assistances. Finally depreciation and interests are related to the size of the airplane, in this case is specially big, so these items take a considerable share of the cost too.

On the other hand it is important to mention the small cost associated to electricity usage. This was one of the hypothetical advantages of a battery powered airplane. Though, that movement is not going to be profitable unless battery technology and costs leap to a different level.

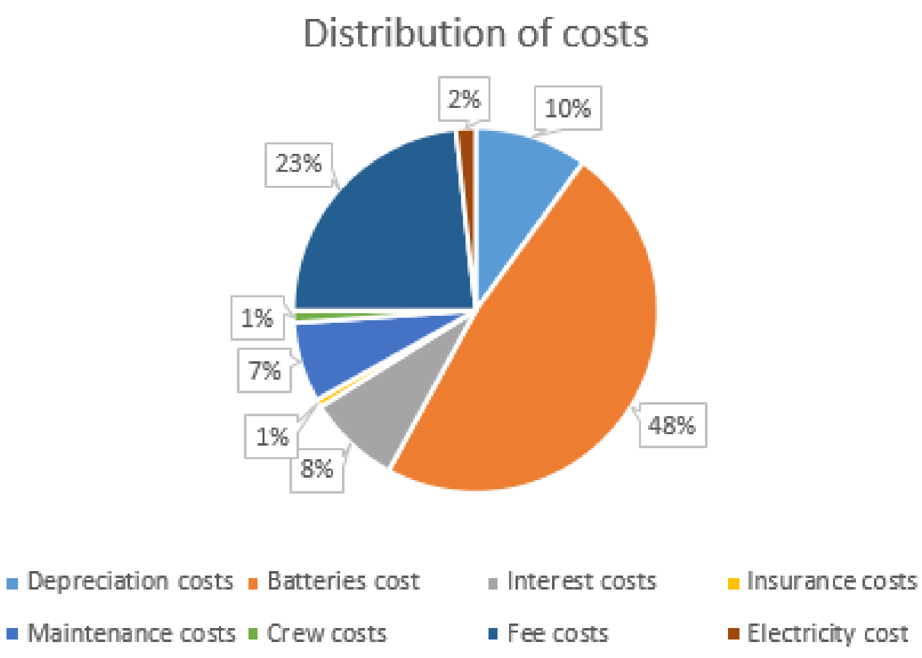

Figure 6.6 Distribution of costs in the battery powered A320.

6.3 How Good do Batteries Need to Become in order to be Feasible?

As it has been already explained, in this chapter is going to be studied the technological and economic aspects of batteries, and how do they have to improve in order to make batteries a real alternative to fossil fuels.

6.3.1 Technical Analysis

For the technical analysis, it has been imposed the same payload requirement to the program than exposed in table 6.2, but also it has been imposed a realistic range, 2000 nautical miles. Now the question changes compared to the previous part of the chapter: What is the minimum quality of batteries that fulfil these requirements?

In the following figure it is exposed the border between the zone where technology makes possible to fly with batteries and the zone where it does not. It has also been represented some values of energy density and specific energy for different kinds of batteries, like current ones, Lithium-Sulfur (specially studied in this text), and another kind of battery, Lithium-Air **(Christensen et al. 2011)**, which has not demonstrated lab values yet and is a technology which only theoretical estimations have been made, being in a very early stage for its implementation yet.

It is quite illuminating that none of this kinds of batteries are beyond the possibilities border, giving a quite hopeless perspective of the possibilities of batteries in aircraft. If requirements are relaxed then it could be possible, but the airplane versatility would be undermined.

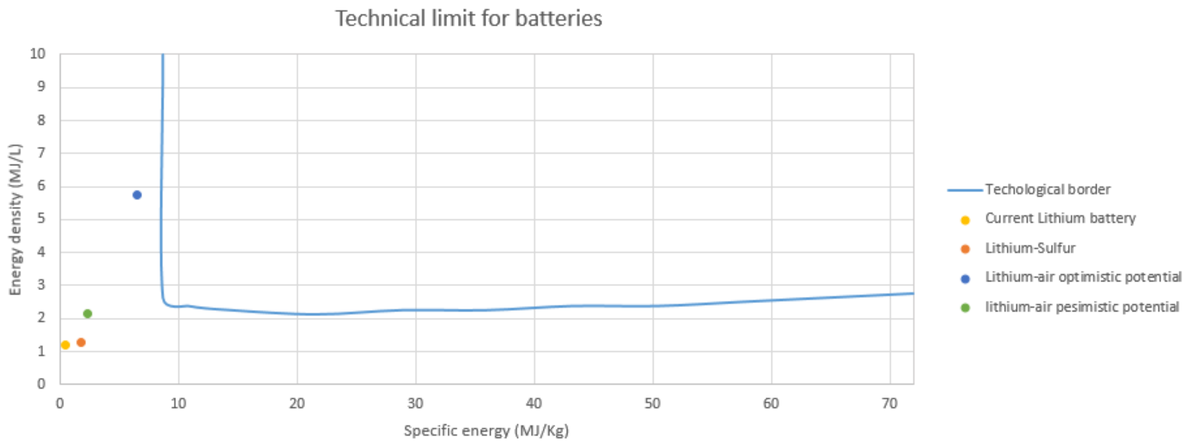

Figure 6.7 Technological border and technological level of different batteries. All kinds of batteries are out of the possibilities area.

In this figure it can be seen two different limitations for the technology in batteries which are slightly coupled. On one hand, the vertical limitation (which is fully vertical and extends to infinite values of energy density, it has only been represented that section to set a better view) is the limitation of weight. In that area space is not a problem in the airplane, but it is weight; landing gear and engines are becoming bigger until eventually design is impossible.

On the other hand, the horizontal limitation is due to lack of space in the airplane to locate batteries. This "line" slightly grows with specific energy because the airplane becomes lighter and there is no necessity of big wings, so storage in wings progressively disappears.

In conclusion, it is unbound that batteries will become a technical alternative to fuel powered airplanes in short and middle term for the requirements here analysed.

6.3.2 Economic Analysis

For the economic analysis some assumptions must be made in order to be able to represent data in a intelligible way. A lot of variables have their influence now, not only specific energy and energy density as before, but also cycles that batteries can work before disposal, electricity price in the wholesale market, price of batteries, and oil price (for comparing with the fuel powered airplane).

In this section the same requirements of payload and range (20186 kg and 2000 NM respectively) have been imposed. Because in the previous section it has been exposed that there is no battery that can possibly fulfil these requirements, another assumption will be made: It will be assumed it will turn out that Lithium-Air batteries will finally be better than the best of expectations, good enough to barely cross the technological border. Because lithium air batteries seem to have a projected density of approximately 900 kg/L, then that would lead us to consider values like

$$s_e = 8.7MJ/kg \tag{6.1}$$

$$\rho_e = 7.8MJ/L \tag{6.2}$$

where ρ_e is the energy density.

In order to make the analysis simpler, electricity costs will be neglected, because they are too small in comparison to battery costs, as shown in section 6.2.3. This finally leave us with only three variables: Battery cost, cycles that batteries can work before disposal, and average oil price (during airplane lifespan).

Considering these three variables, it can be represented the economic border for batteries, but it has to be remembered that in the list of hypothesis, some strong assumptions were made in costs, so this line will only represent the border where a commercial battery-powered airplane can start to be considered.

In the following image then, the battery-powered airplane starts being profitable bellow the corresponding oil price line, depending on the oil price in the moment of comparison.

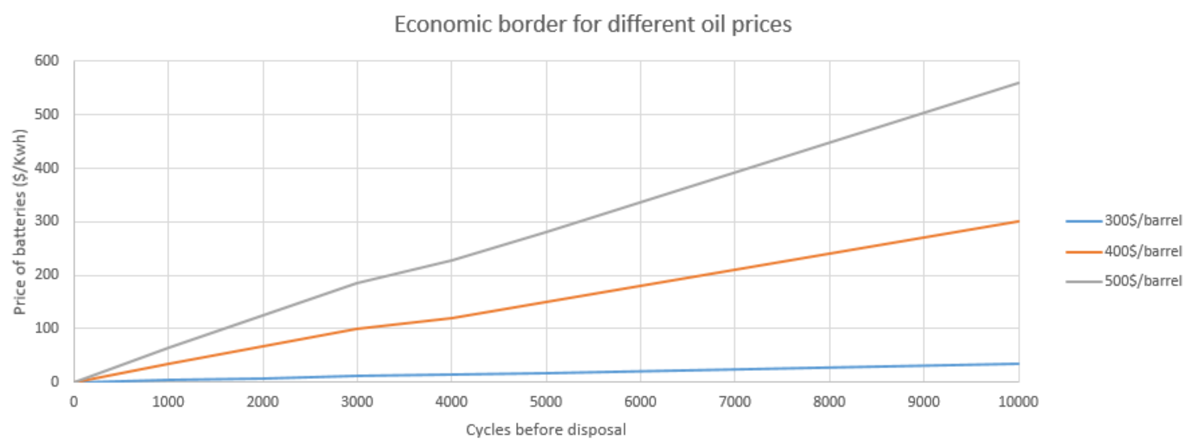

Figure 6.8 Economic border for different oil prices. Because it is being assumed a kind of battery which is due to appear in a far future, different average oil prices are considered.

As it can be observed, even though all the optimistic hypothesis made, and considering an outstanding technology in Lithium air batteries, the battery powered airplane starts to be profitable in values between 300$/barrel and 500$/barrel (lines bellow 300$/barrel would only appear if it is considered negative battery prices, which does not make sense), which is between four and six times bigger than the current price. In this unlikely case an hypothesis like neglecting electricity price does not make sense (in this scenario it would surge), leaving things even worse for our battery powered A320.

7 Summary and Conclusions

It is safe to say that battery powered airplanes are technically an alternative and it will be possible to fly with them in a close future, but only in extremely short distances, being their range strongly limited.

Though, it has also been shown that, despite it is possible to fly just with batteries, they are a prohibitive alternative in economic terms. Experience shows us that ecological alternatives must be minimally efficient in terms of profitability and market efficiency, otherwise these alternatives will give an excuse to powerful lobbies, like oil lobby, to criticise the whole ecological movement and mark their solutions as ruinous. From the economic study made in this text, it can be firmly stated that battery powered airplanes for commercial transportation will not be a realistic alternative in the short and middle term, specially when taking into account alternatives like High-speed rails, which can be fed directly from the grid using green energy, are very automated, and have a much brighter potential when talking about magnetic levitation.

It is important to mind that it has not been considered neither the tremendous investment in infrastructure that would be necessary in order to adapt airports to this new technology, nor the new procedures and safety measures due to be implemented if the became real (with an associated cost). This only gives us an even more hopeless perspective of battery powered airplanes.

The effect of weight in aircraft performances is crucial and determines its efficiency. Because batteries are not dumped while used as kerosene is, this effect is broader as long as longer is range. Although this also opens a new window for this kind of technology: Inventions like civil drones, which are likely to be regulated to not produce noise and would have a very low endurance requirements are aircraft where this technology could fit much better, specially taking into account that standard airplane engines reduce their efficiency (Due to increment of viscosity effect, or in other words, lower Reynolds number) and weight-to-power ratio when they become smaller (due to duplicities in the system).

If we talk about different green alternatives for commercial aircraft design, then it is necessary to consider other possibilities like biofuel or hydrogen generated with renewable energies, alternatives of energy storage that do not suffer from such a low specific energy like batteries do, allowing to lighten airplanes given the importance of weight.

In other kinds of transportation, weight is not as crucial as it is in lifting airplanes. Nowadays, a re-introduction of the electric car is been performed all around the world, and it is likely to keep pushing forward, turning the modern transportation into a much more sustainable reality.

Anyway, it is clear that large investments in battery technology are coming, and with them, new ways of eco-friendly transportation will come. In the case of commercial airplanes, substitution of old hydraulic system for electronic control systems will be surely implemented in the future.

8 Recommendations

Some ideal hypothesis have been assumed in order to simplify this study and make it affordable in time. Conclusions are clear and leave no room for error, and making more complex models would have brought the same judgement, having just more precision in determining the gap that lies between actual batteries and its necessary level of technology that would make them a possible alternative. However, a very first recommendation would be to implement these more precise models (like, for example, real engine hypothesis) because they can be helpful to study other kinds of alternative technologies based on electricity.

Along this work, it has been observed the tremendous effect of having the source of power (batteries) in the airplane the entire flight. This sets a big handicap for the possibilities of an airplane equipped with a system like this in comparison to fuel powered airplanes, where weight is being reduced along the flight.

In this line, it would be advisable to study the opposite system, a system where the energy is consumed at the same time it is provided to the airplane; A good example would be a solar powered airplane. Solar panels are becoming rapidly cheaper with time, so it could be interesting its study, with some batteries covering the fluctuations coming from variations in the exposure to sun.

Two different and interesting studies could come from this idea:

On the one hand, it is attractive the idea of studying autonomous drones equipped with this technology, showing its feasibility and characteristics. Their short range and the freedom in their design leave room for innovation and optimization.

On the other hand, another idea could be to integrate solar panels in commercial transportation airplanes to supply aircraft systems, such as air conditioning and electronics, with batteries absorbing fluctuations in the energy c atchment. This can lead to better efficiency because now it would not be necessary to take that energy from burning extra fuel in the engine.

There is another work line that could be addressed in the future, and it is concerning to ecology. It has been seen that battery powered airplanes are so heavy that they become very inefficient, wasting a huge amount of energy for just moving few miles. Concerning this matter, the idea of determining whether a battery powered airplane can be an ecological alternative or the opposite; a waste of resources and fossil fuels used to supply it with electricity.

If this analysis is performed, the main point would be to decide how much it is obtained from the ecological point of view, how many tons of CO2 are saved to the atmosphere per year. It is fair to say that it is possible that the answer to this matter could be unpleasant even in this particular point.

If that happens, it is interesting to arise other questions to the air: How good batteries need to become in order to become ecological? It is clear that this question has a different answer for different ranges, because as it has been widely commented, batteries are not compatible with long distances.

Coming from this point, those values could be compared to forecast values for a near future. In consequence, a proper answer to the ecological point would be reached.

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Appendix A - Principle of Operation of Batteries

In this appendix it is going to be explained how batteries work in very basic terms. Of course, if the reader needs more information, there is a broad variety of bibliography that can be consulted.

Electricity is usually seen as a flow of electrons (actually it is not exactly like that) along a electromagnetic path, like a wire. In consequence, batteries create a difference of density in electrons between two points connected by a wire, so the system will tend to equilibrate itself by a flow of electricity through that wire. That flow of electricity and its intrinsic energy could be used to turn a light on, for example.

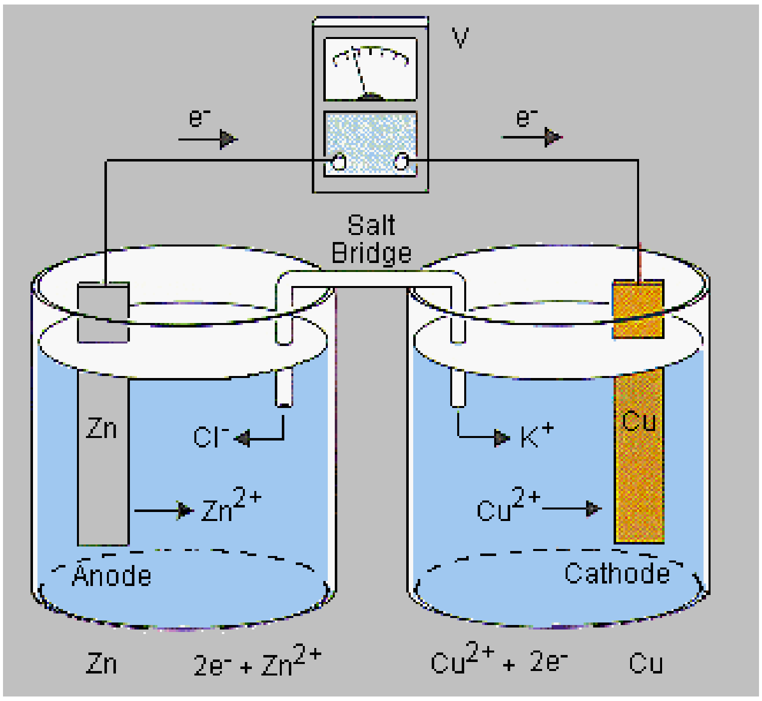

Figure 8.1 Zn-Cu Battery scheme. Chemical reactions in both sides create a difference of electromagnetic potential, causing electricity to flow. Image taken from **KidsEnergy (2005)**

As it is shown in the image, chemical reactions in the cathode and the anode cause a flow of electrons through the wire. In consequence, chemical energy is being transformed in electrical energy.

This process can be reverted by adding electric energy back to the system, this energy would cause the chemical reactions to go in the opposite direction, so the battery can be used more than once.

Appendix B - Introduction to Basic Aerodynamic Equations

It is important to mind the nature of aerodynamic equations in order to set a profound understanding of how the air relates with the wing and which variables influence that process. The basic equations are then going to be exposed, and explained, but not demonstrated. The demonstration is well exposed in several books of aerodynamics, for instance, **Meseguer and Sanz (2005)**.

$$L = \frac{1}{2}\rho V^2 S C_L \tag{8.1}$$

$$D = \frac{1}{2}\rho V^2 S C_D \tag{8.2}$$

These equations are basically expressing the same reality with a dimensionless coefficient, which contains the influence of the airfoil shape, air friction, angle of attack, and air compressibility.

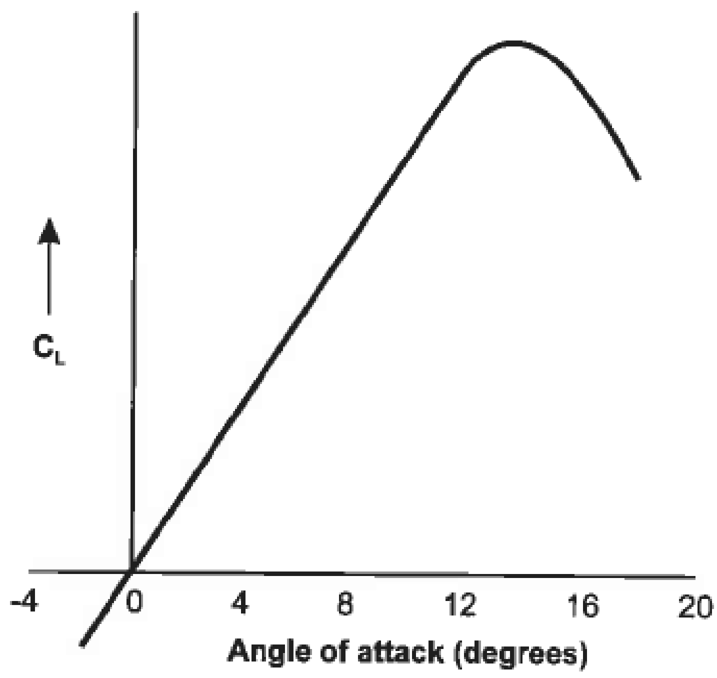

Figure 8.2 Evolution of the lift coefficient with the angle of attack. Image taken from **Rotorhead8900 (2011)**

If ideal hypothesis are made (such as no air viscosity, no turbulence, steady subsonic airflow and no separation of flow), it is found that C_L has a very simple expression

$$C_L = \frac{2\pi}{\sqrt{1-M_0^2}}\alpha \tag{8.3}$$

Where α is the angle of attack of the airfoil. This expression is a big simplification and leaves us with a linear hypothesis. Actually, when an airfoil is placed in the wind tunnel it sheds data that confirms this equation, but only for moderated angles of attack; for big angles of attack the airfoil gets into stall and lift decreases rapidly.

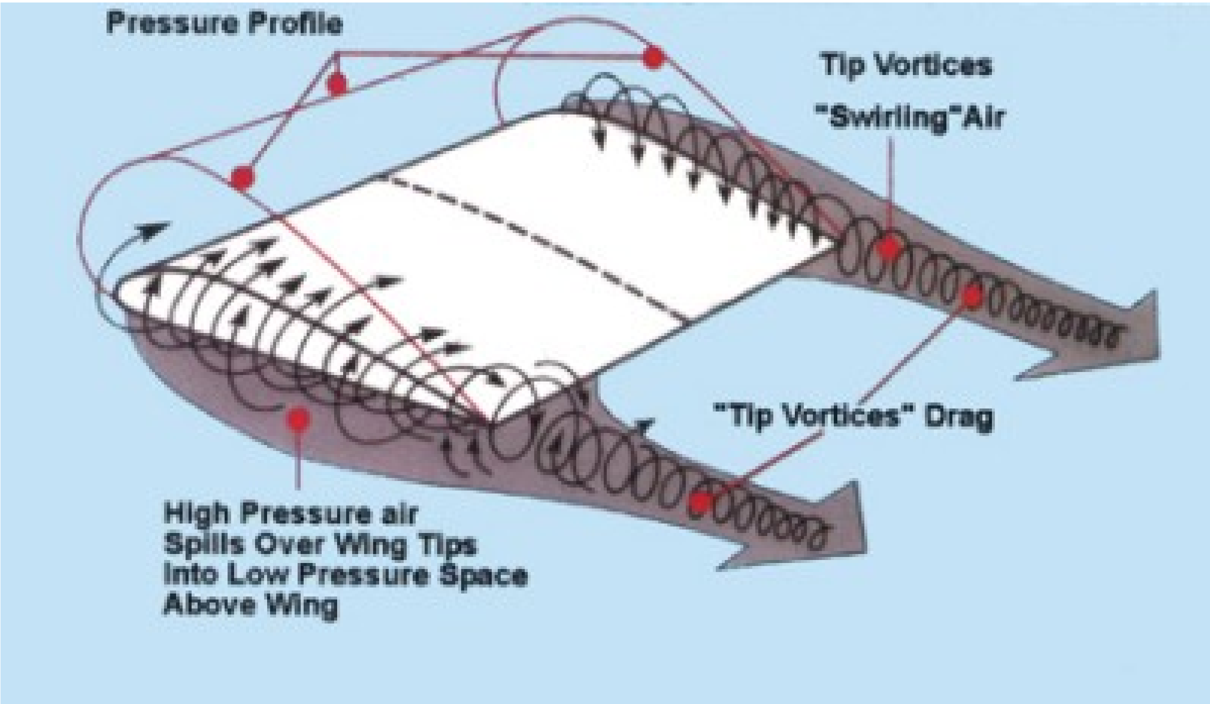

Figure 8.3 Wingtip vortices generated by the difference of pressure between the two parts of the airfoil. Image taken from **Pilotfriend (2000)**

For the drag coefficient there is another simplified model, called the parabolic polar model. This model assumes that C_D varies with C_L in the following way

$$C_D = C_{D0} + kC_L^2 \tag{8.4}$$

Where sometimes it is implicitly written that $k = \frac{1}{\pi A \varphi}$.

This equation sets a crucial relation between lift and drag, and its consequences are drastic. It means that a heavier airplane will need a larger lift to stay on air, so it will also suffer a larger drag force. This is why it is so important to design light airplanes; it increases efficiency of flying dramatically.

The reason for this coupling between C_L and C_D is mainly the induced resistance. Wingtip

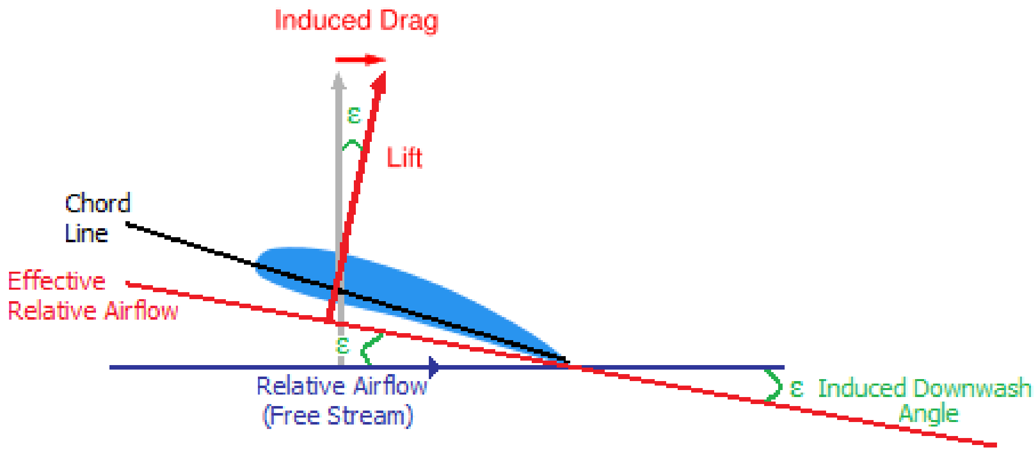

Figure 8.4 Lift is proyected against the airplane velocity, generating induced drag. Image taken from **Walton (2013)**

vortices generated by the difference of air pressure between the upper part of the wing and the lower part of it generate an induced angle of attack not perpendicular to the airplane, which in practice, generates an induced drag that becomes larger as the lift does.

Appendix C - Maximum Take-Off Weight Calculations in OPerA

In the tool OPerA, calculations of take-off mass are slightly different than exposed in section 4.4. In this program there is no estimation of the quotient of Operative Empty Mass divided by Take-Off Mass, $\frac{m_{OE}}{m_{MTO}}$, but a direct estimation of the Operative Empty Mass, m_{OE}.

So now inputs are

- Operative Empty Mass (Estimation), m_{OE}
- Payload Mass (requirement), m_{PL}
- Percentage of batteries in Weight (Coming from range requirement) $\frac{m_{bat}}{m_{TOW}}$

Now it is very simple to operate with those inputs to finally get the m_{TOW}

$$m_{TOW} = m_{bat} + m_{PL} + m_{OEW} = \left(\frac{m_{bat}}{m_{TOW}}\right) m_{TOW} + m_{PL} + m_{OEW} \tag{8.5}$$

Which easily lead us to

$$m_{TOW} = \frac{m_{PL} + m_{OEW}}{1 - \left(\frac{m_{bat}}{m_{TOW}}\right)} \tag{8.6}$$

It is important to mention that, in the program, the estimation of m_{OEW} is made based on the estimation of m_{TOW}, so there is a feedback in this calculation process that eventually leads to an equilibrium point (unless requirements are impossible to fulfil, in that case the process would be divergent). For example, it seems obvious that the landing gear mass, which is included in m_{OEW}, is strongly influenced by m_{TOW}.